ANALYSIS OF A PROPOSED DIFFERENTIAL OMEGA SYSTEM

by

Michael Eugene McKaughan

United States
Naval Postgraduate School

THESIS

ANALYSIS OF A
PROPOSED DIFFERENTIAL OMEGA SYSTEM

by

Michael Eugene McKaughan

December 1970

Analysis of a Proposed Differential Omega System

by

Michael Eugene McKaughan
Lieutenant, United States Coast Guard
B.S.E.E., California State Polytechnic College
Kellogg Campus, 1966

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1970

ABSTRACT

Omega, a world-wide, VLF, CW, all-weather navigation system offers one mile resolution, but suffers in accuracy due to propagation anomalies which have been found to be relatively constant over differential areas. Differential Omega is the process of disseminating propagation-produced error to users in the differential area. Accuracy improvements of 5 to 1 are possible.

A system of Differential Omega using a Coast Guard Radiobeacon was proposed by Goodman. His system has been reviewed and improvements suggested. The correction message format was reviewed and changed to include line of position (LOP) identification. A revised transmitting scheme using a master oscillator controlled frequency synthesis process with digital readout is evaluated. Using the frequency synthesized master oscillator controlled Differential Omega system, accuracies of 30 yards can be realized for idealized Omega receiver inputs.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

A. THE OMEGA NAVIGATION SYSTEM

1. History

Throughout history seafarers and travelers have sought a means of locating their position and of navigating vessels on the earth's surface. While searching for an adequate solution to this problem, navigators have established these requirements: 1) all-weather usage, 2) world-wide coverage, 3) reasonable accuracy, 4) simple operation. Various systems have been developed to fill these requirements, but no single system has been capable of completely satisfying all of them.

a. Celestial Navigation

One early navigation technique which is still in wide use is celestial navigation. Since it uses the positions of the sun and stars to acquire fixes, it does not provide all-weather navigation. Furthermore, fixes are seldom more accurate than a few miles and methodic calculations are required.

b. Electronic Navigation Systems

(1) Loran A. The development of electronic navigation systems was a great step toward an ideal system. Loran A is a World War II developed system which transmits pulses of radio frequency energy at approximately two megahertz. Transmitting station pairs are received to give hyperbolic lines of position by measuring time-of-arrival differences. Although

Loran A offers all-weather navigating capabilities, the ground-wave propagated signal cannot be reliably received beyond approximately 100 nmi. Another disadvantage of this system is the method of measuring the time-of-arrival delay. By matching only the pulse envelopes of the received signals, accuracies are limited to several miles.

(2) Loran C. An improvement on Loran A is the Loran C system. Operating at 100 kHz, the time-of-arrival delays are measured by matching the phase of the radio frequency carrier within the pulse envelope. The lower frequency ground-wave transmissions propagate nearly 600 nmi before being contaminated by skywaves. The accuracy of Loran C is on the order of a few miles.

(3) Other Systems. Decca is a commercial system which uses harmonically related frequencies to transmit continuous wave (CW) signals. This system does not give world-wide coverage and has the disadvantage of possible ambiguous fixes. Loran B was a high accuracy small-area version of Loran A which never reached implementation. The main reason for non world-wide coverage by these systems was limited propagation characteristics at the selected operating frequency.

2. The Radux Propagation Studies

Radux was a low frequency (LF) experimental navigation system which historically preceeded the installation of Loran C. Radux is important since extensive LF propagation data were collected through system tests. Operating initially at 100 kHz, the frequency now used by Loran C, Radux experiments indicated

that a lower frequency would have propagation characteristics more favorable to navigation systems. Lowering the operating frequency to 40 kHz verified previous indications and revealed promise of better results at lower frequencies. As an outgrowth of Radux experiments and the shortcomings of previous systems, a very low frequency (VLF) CW navigation system, called Omega, was proposed which would operate in the 10 to 14 kHz frequency band. Experimental Omega transmitting stations are set up and the concept tested. The sites chosen were selected because of existing antennas instead of optimum system configuration considerations. The temporary system, with sites in California, Hawaii, New York, the Panama Canal Zone, and Wales [1] was used to make signal measurements at widely distributed locations. These measurements proved that readings could be predicted accurately enough for 1) Omega Charts to be plotted, 2) system range and accuracy to be determined, and 3) expected operational reliability to be measured. Armed with the results of these tests, it was recommended that Omega be implemented as an operational navigation system. [2]

3. The Present System

In the Omega System, eight strategically located VLF transmitting stations blanket the world with a grid of hyperbolic constant phase-difference contours which allow a navigator anywhere on the globe to determine his position within one mile by day or two-to-three miles by night. Each transmitting station emits a CW signal about one second out of every ten.

All stations transmit sequentially on precisely the same frequency; transmissions are phase-locked to a common time standard.

a. System Geometry

One of the chief disadvantages of past hyperbolic navigation systems has been the divergence of contours with increased distance from the transmitters. This can be seen in Figure 1. Two stations, A and B, transmit signals which are compared on an arrival time or arrival phase-difference basis. On the base line - an imaginary line running from station A to station B - there is a fixed distance between equal step changes of times-of-arrival or phase-difference. As a user leaves the base line and travels farther away from the station pair - toward point C for example - the contours of constant time-of-arrival or constant phase-difference diverge and the distance between two contours increases. At the edges of the service area, the distance error associated with a fixed time-of-arrival or phase-difference measurement error is far greater than near the base line.

Another disadvantage of earlier systems was limited propagation characteristics. Signals of sufficient strength could not be generated to allow base lines long enough for world-wide coverage from a reasonable number of transmitting stations. Omega transmissions - at 10 to 14 kHz - can be reliably tracked over an average range of 7000 nmi. With such extensive coverage and the accompanying possibility of base lines which are an appreciable fraction of the earth's circumference, as few as six transmitting stations can give world-wide

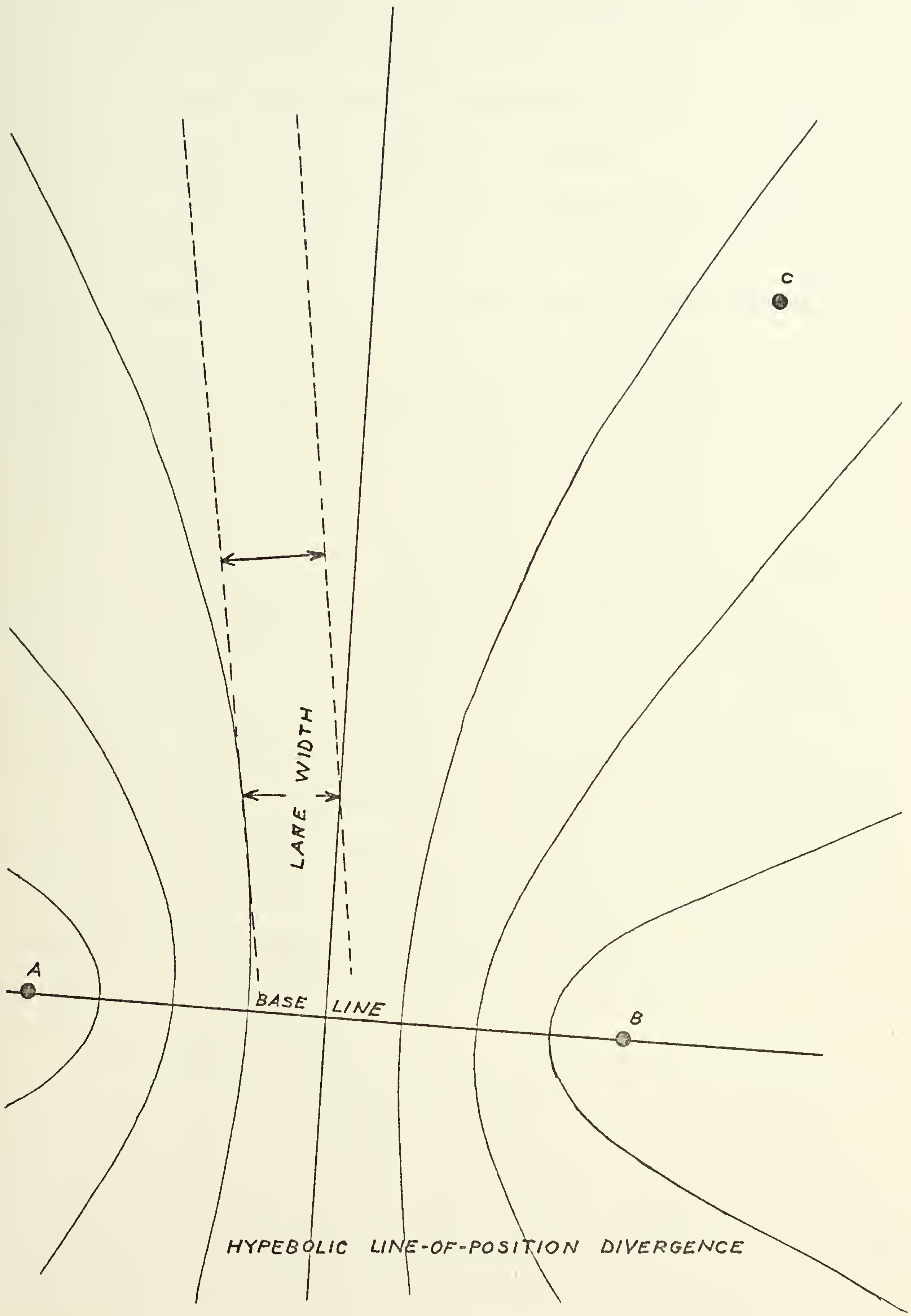

C
LANE WIDTH
A
BASE LINE
B
HYPEBOLIC LINE-OF-POSITION DIVERGENCE

FIGURE 1

coverage and still not introduce appreciable system errors resulting from phase-difference contour divergence. Of course, these six transmitters must be carefully placed to assure the coverage of which the system is capable.

The ideal transmitting configuration is one station at each of the verticies of the earth's octants. This particular configuration requires transmissions be omnidirectional and usable to at least 5400 nmi. Here the phase-difference contours diverge only slightly and lines of position cross at nearly right angles due to the long base lines and optimum station placement.

Transmitter malfunctions could result in unreliable fixes when a navigator is forced to use weak signals from a remote station. With the addition of two more transmitters the system redundancy would be improved so that five usable lines of position would be available to a navigator anywhere on the globe under normal transmitting conditions. With up to three transmitters non-operational, a navigator would still be able to receive three lines of position (LOP's). The present eight-transmitter Omega system thus gives redundant world-wide coverage.

b. Signal Format

The present Omega system is unique in the sense of transmission mode and station relationships to one another. Omega is a CW system (as is Decca) and all stations transmit on precisely the same frequency (as in Loran C). The apparent impossibility of transmitting eight CW signals at precisely

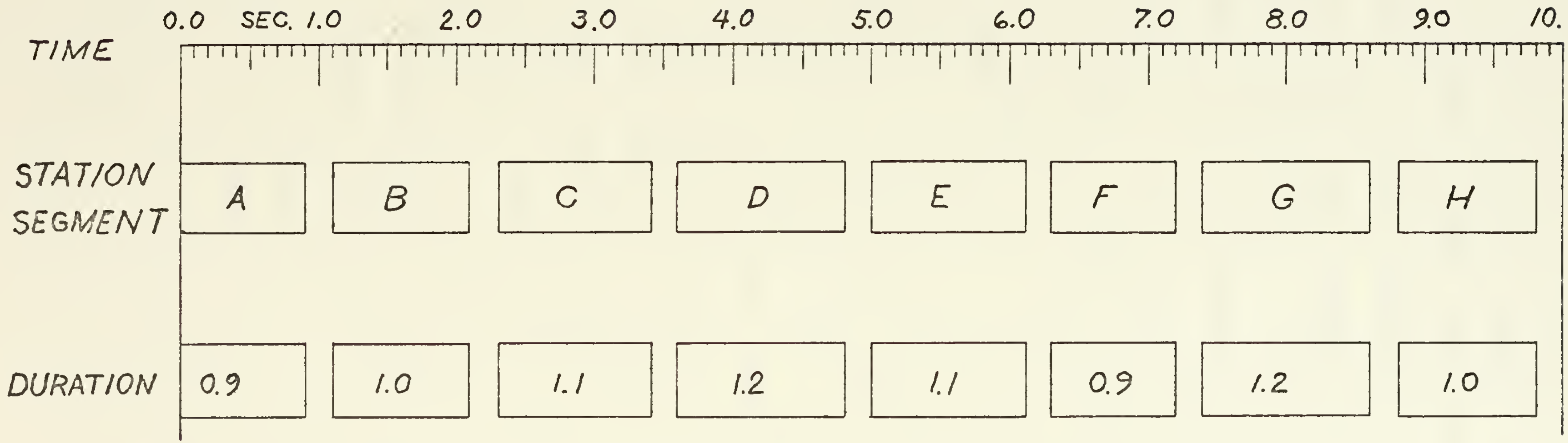
the same frequency is overcome by using a time-multiplex scheme where stations transmit sequentially for approximately one second of a ten second interval.

The transmission sequence is designed to enable the user to identify each individual station. A transmitter signature consists merely of the length of the transmission interval and its position in the sequence with respect to the other stations. Figure 2 illustrates the time-multiplex scheme used. To identify station C, the user would locate the 1.1 sec pulse preceeded by a 1.0 sec pulse and followed by a 1.2 sec pulse. Thus station C can be distinguished from station E which also transmits a 1.1 sec carrier. This timing sequence allows the use of both manual and completely automatic receivers.

The psuedo-pulsed CW Omega signal has advantages over other navigation system signals. At VLF the extreme narrow bandwidth of the antenna system limits the pulse rise time to a few cycles of the carrier signal. The long - one second - pulses thus have ample time to attain full amplitude and the system is not hampered by band limited pulses. By operating at a single frequency, internal receiver phase shifts are common for all signals and these phase shifts need not be known or calibrated.[1]

---

[1]It will be shown later that Omega uses multiple frequencies in order to resolve the lane ambiguities of the CW system. Single frequency here means that a given receiver operates on only one channel during a given time period.

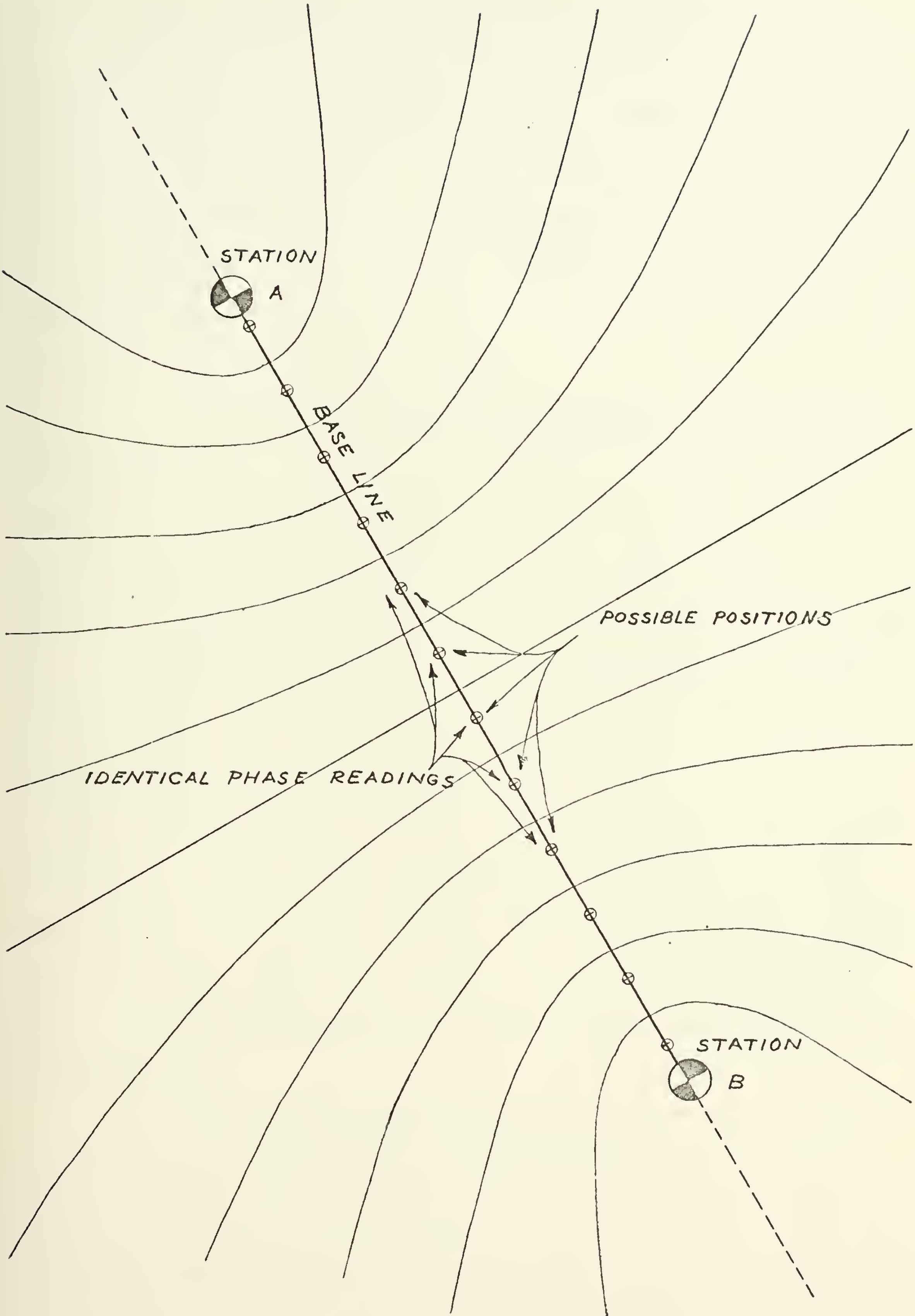


OMEGA TRANSMITTING TIME-MULTIPLEX SCHEME

FIGURE 2

An obvious system problem is the fact that phase comparisons must be made between signals which do not exist simultaneously. In order to make the necessary comparisons, each incoming signal is phase compared to a stable internal oscillator. Phase comparisons between two stations are made using their relative comparisons to the internal standard.

A disadvantage of CW navigation systems is that position fix ambiguities result because phase can only be resolved into 360° blocks. Figure 3 illustrates this situation. Assume that a vessel is travelling along the base line from station A to station B. As the ship travels one half wavelength toward B - 15 km for an operating frequency of 10 kHz - the phase of the received signal, compared to the receiver internal standard oscillator, will decrease by 180°. At the same time the received phase comparison for station A will increase by 180° since the ship has moved one half wavelength away from that station. The resultant phase-difference is 360°. As the ship continues toward station B, the phase-difference will repeat a complete 360° shift for every one half wavelength travelled along the base line. Since the electronic circuitry within the receiver can resolve phase differences to only 360°, the navigator cannot tell which 360° group he is in without additional information. In CW navigation systems the 360° phase difference groups are referred to as lanes and the position ambiguity just described is known as lane ambiguity. In Omega, the lane width is 15 km on the base line between stations. For a navigator to accurately fix his position he



LANE AMBIGUITES ON THE BASE LINE
FIGURE 3

must know his location to within plus or minus one half a lane width (7.5 km or about 4 nmi) in the worst case. The required fore-knowledge becomes less as a ship moves away from the station pair base line. This illustrates the system difficulties resulting from the CW transmissions. The methods used in Omega to resolve the lane ambiguities will be discussed in a later section.

c. System Synchronization

(1) Master-slave Synchronization. Initially the Omega system used a master-slave concept to synchronize transmissions of the experimental stations. In master-slave operation one station, called the master, is selected as a reference. The other stations receive the master signal and phase-lock their transmissions to it. This type of system requires that all stations be capable of receiving and maintaining high quality phase information from the master. For the initial Omega concept tests, the master-slave arrangement worked well. But, as the world-wide capabilities of Omega were realized, it became obvious that a single master station could not serve Omega slave stations over the entire world. A more reliable and accurate means of system synchronization was mandatory.

(2) Free-running Synchronization. The timely availability of ultra stable precision atomic oscillators offered a solution to the synchronization problem. These oscillators made feasible the concept of a free-running system in which stations operate independent of each other. Synchronization between stations in the system is maintained by having

each station lock their transmissions to their own stable frequency source. The stable frequency source is the average frequency of four high stability cesium oscillators. As a check on system synchronization, monitor stations compared phase-differences between all possible pairs of received signals. If any one station drifts beyond tolerance limits, corrections are ordered to the erring transmitter.

d. Lane Identification

As indicated above, Omega suffers from the lane ambiguity problem characteristic of all CW navigation systems. This ambiguity is a result of the periodicity of the transmitted signals. An example, while not Omega, will serve to illustrate the lane ambiguity problem.

(1) An Example of Lane Ambiguity. Suppose two ships are travelling in formation one directly astern of the other. The formation is homing on a VLF CW transmitter operating at 10 kHz. Both ships are keeping station by comparing the phase of the received VLF signal with the phase of an on-board standard oscillator at the same frequency. Solely for purposes of illustration, assume that the two shipboard oscillators are in absolute phase synchronization. The following ship determines his distance from the leader by observing the phase-difference between his oscillator and the phase of the CW transmissions, and compares this difference with the leader's phase-difference. The ambiguity problem arises when the following ship is required to maintain station exactly one wavelength astern the leader. This means that both ships

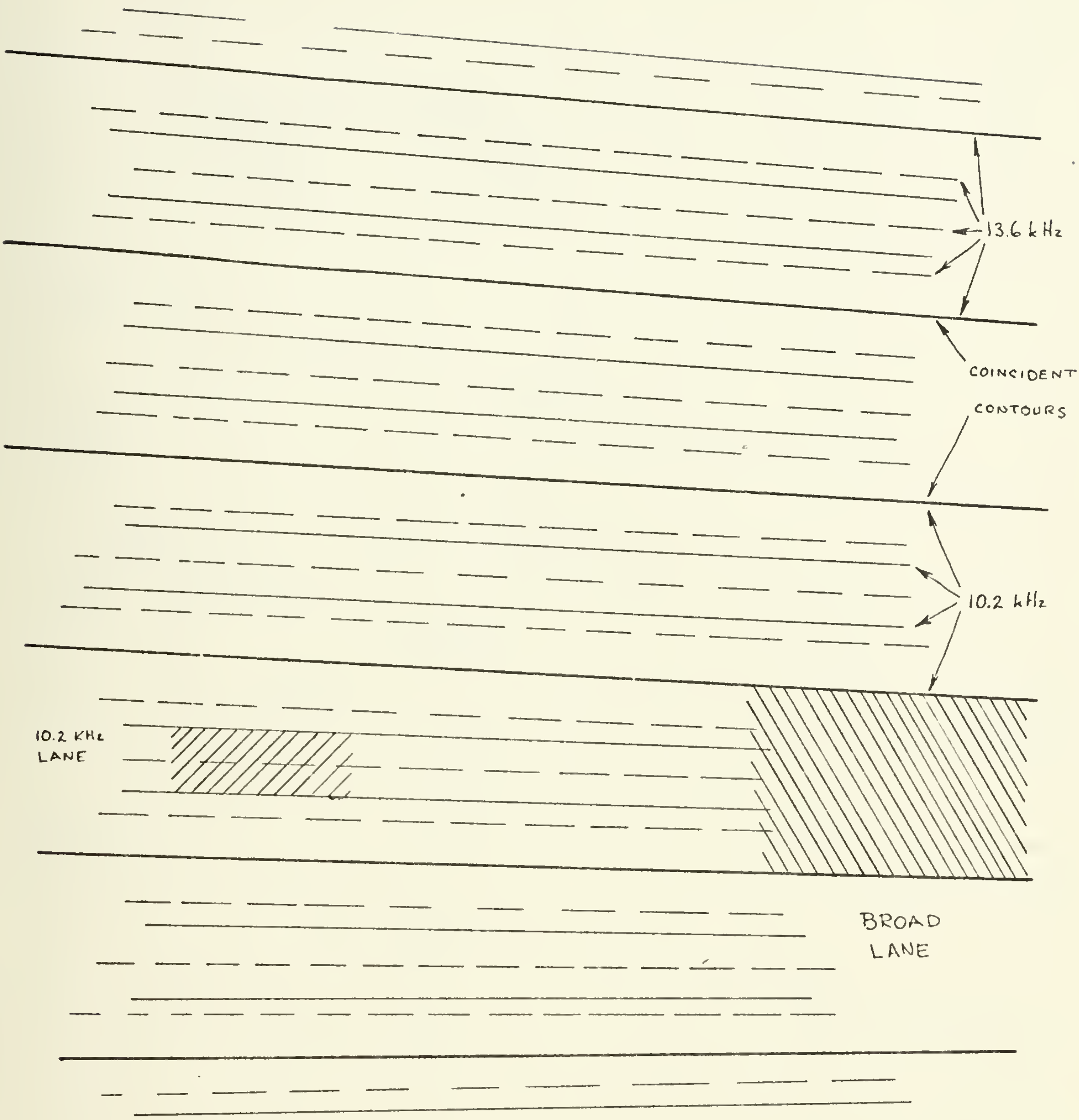
observe identical phase readings. In reality the two could be any integral number of wavelengths apart and still observe similar readings. Thus the following ship is not certain of the exact number of wavelengths he is from the leader without some outside information be it Radar, dead reckoning, visual contact or any other input. The multiple position ambiguity of the following ship is known as lane ambiguity.

In Omega, the received phase of two stations is monitored. As discussed earlier, relative phase comparisons can only be resolved to 360°. For the two station case, this amount of phase shift occurs for a position change of one half wavelength (as short a distance as 8 nmi on the base line). In order to make use of Omega on a world-wide basis some method must be used to resolve the lane uncertainty.

(2) Lane Counting. There are several possible methods of lane resolution. First, by starting at a known location or home port, it is possible to record each lane as it is traversed with a lane counting device. For a ship at sea or a slow moving land vehicle, this method is sufficient so long as the starting point is known. In an aircraft, some form of automatic lane counting system is required since the crew must be attentive to many other tasks. A submarine which has been out of radio range for an extended period of time could not use a lane counting scheme to resolve lane ambiguities. Thus lane counting is not a universal solution to the problem. Second, lanes may be resolved by using multiple transmitting frequencies.

(3) Using Multiple Frequencies. For the single frequency Omega system operating at 10.2 kHz, the user must be able to independently established his position within plus or minus one half a lane width (4 nmi on the base line). By introducing transmissions at frequencies integrally related to the basic frequency, it is possible to increase the width of the unambiguous lane and hence, reduce the required accuracy of the independent navigational fix. Such an integrally related frequency is 13.6 kHz, four-thirds (4/3) the basic 10.2 kHz frequency. The 13.6 kHz transmissions form phase-difference contours about the station pair which differ from the 10.2 kHz lines only by the fact that the wavelength of the new transmissions is three-fourths that of the basic wave-length. Thus, when traversing three 10.2 kHz lanes, one crosses four 13.6 kHz lanes. Every third 10.2 kHz lane is coincident with a 13.6 kHz lane so that the second order unambiguous lane width is now three 10.2 kHz lnaes or, at the base line, 24 nmi. Figure 4 shows the arrangements of lanes for these two transmitting frequencies. Figure 5 demonstrates how the lane ambiguity would be resolved for the two frequency system. Assume that the received signal for the 10.2 kHz transmissions gives a phase reading of 50 centicycles.[2] Simultaneously, the 13.6 kHz signal is observed to be 100 cec (zero is the same reading). Finally, assume that a celestial fix places the user in the position A. The possible LOP's for

[2] A centicycle (cec) is one one hundredth (1/100) of a cycle of the radio frequency carrier. At 10.0 kHz, the period of the wave is 100 microseconds so one centicycle would be 1.0 microseconds.

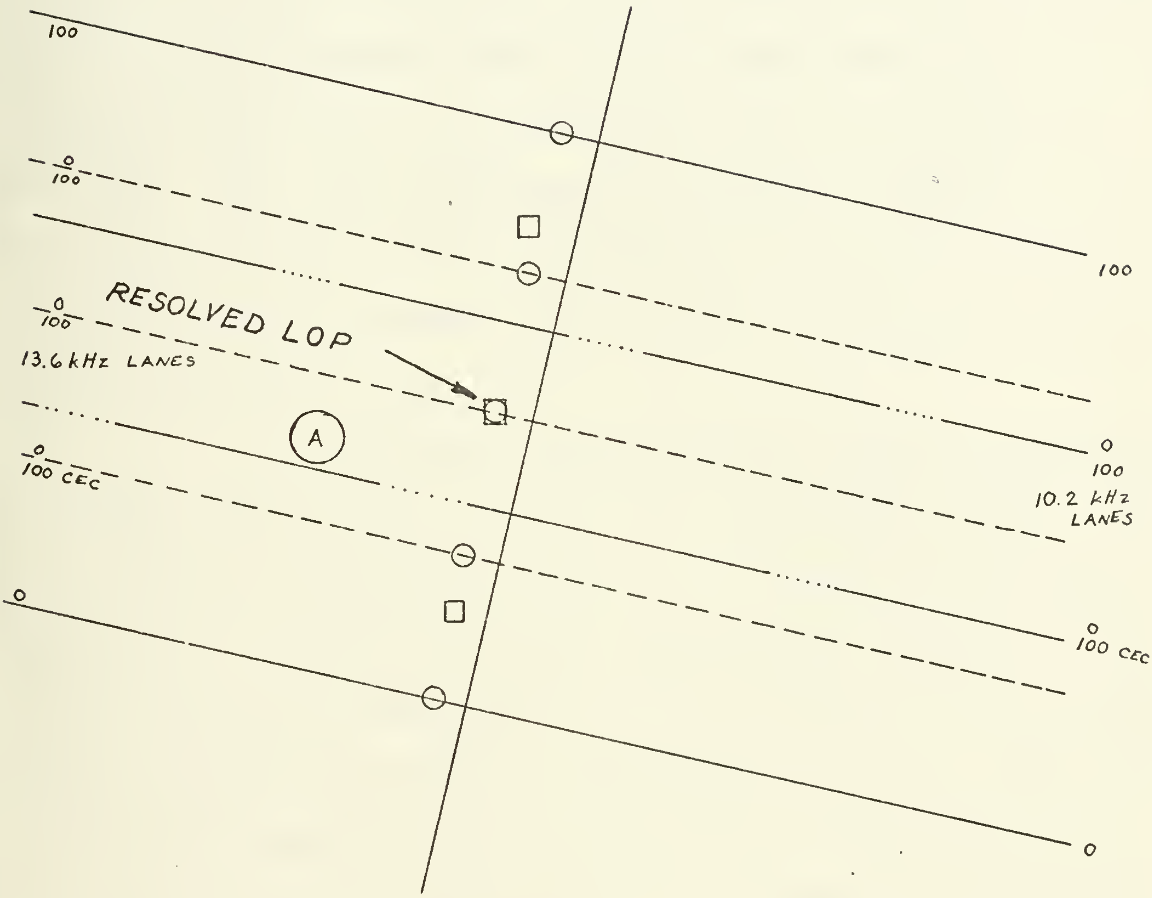


TWO FREQUENCY LANE ARRANGEMENT

FIGURE 4

RECEIVED SIGNALS

10.2 KHZ	50 CEC
13.6 KHZ	100 CEC



Ⓐ CELESTIAL FIX

○ POSSIBLE 10.2 KHZ LOP'S

□ POSSIBLE 13.6 KHZ LOP'S

RESOLVING THE LANE AMBIGUITY WITH TWO FREQUENCY TRANSMISSIONS

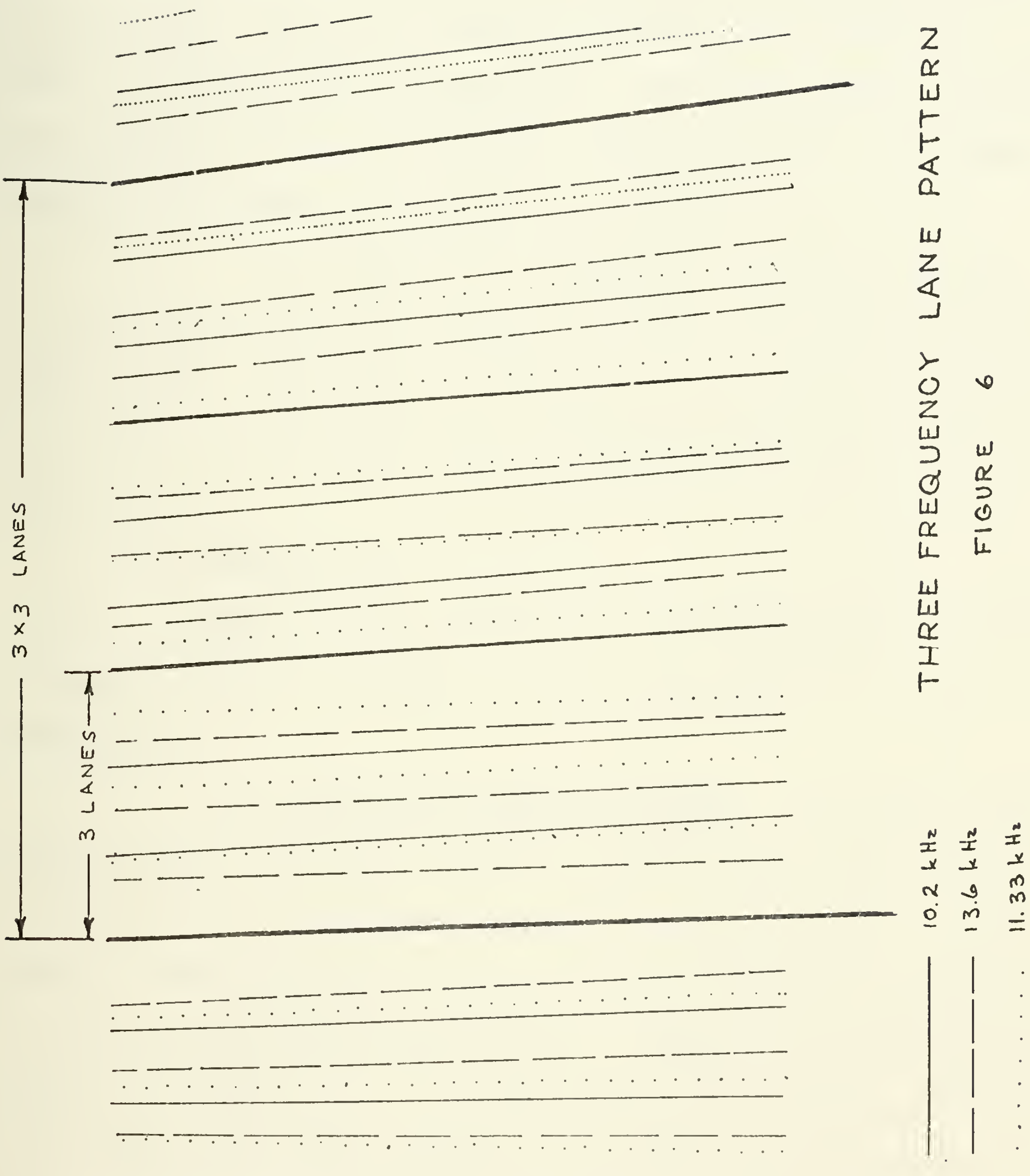
FIGURE 5

each frequency are plotted and the position LOP is the one common to both frequencies.

A further widening of the unambiguous lane width comes about upon addition of a third transmitting frequency. This third frequency of 11 1/3 kHz is ten-nineths the basic 10.2 kHz frequency. Just as for the 13.6 kHz lanes, the 11 1/3 kHz lanes and the 10.2 kHz lanes form a set of interwoven lanes with an unambiguous width of 72 nmi on a base line. This lane arrangement is shown in Figure 6. In nearly all practical cases a minimum position ambiguity of $\pm$ 36 nmi would give enough margin so that the correct 10.2 kHz lane could be found.

A desirable system feature might be the ability to resolve any ambiguity entirely from the Omega system. One way to do this would be to apply a low percentage amplitude modulation to each of the three transmitting frequencies and use the modulation frequencies to further reduce the ambiguity. Possible frequencies would be 226 2/3 Hz on the 13.6 kHz signal to extend the unambiguous base line lane to 360 miles, 45 1/3 Hz on the 11 1/3 kHz signal to give an unambiguous base line lane of 1800 nmi and 11 1/3 Hz on the basic 10.2 kHz signal for a 7200 mile wide unambiguous base line lane. This shows that it is possible to completely resolve the lane ambiguity solely with the Omega system.

(4) Multiple Intersections. Another method which could be used to resolve the lane ambiguity is called multiple intersections. This idea makes use of the system ability to



THREE FREQUENCY LANE PATTERN

FIGURE 6

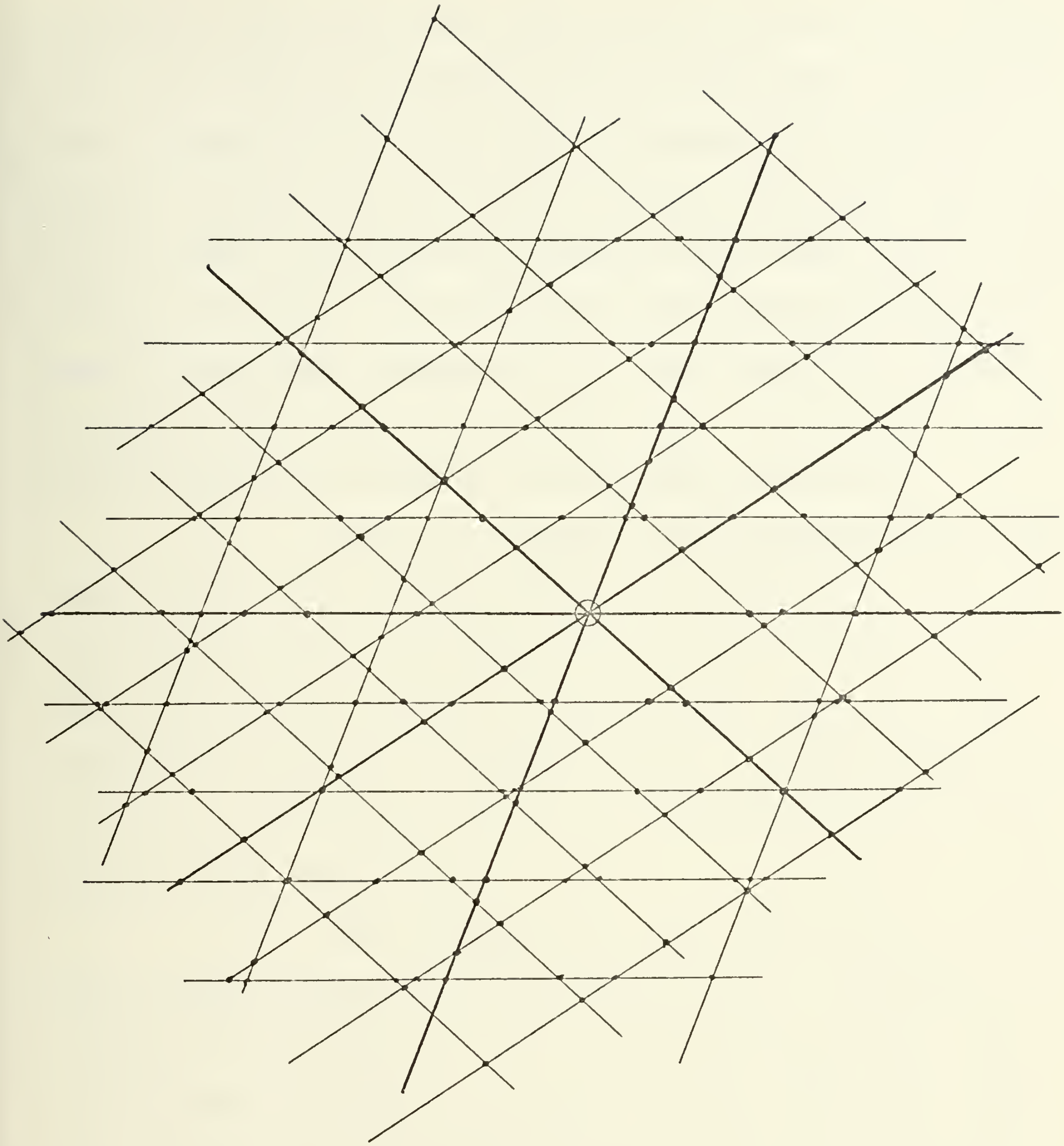
receive at most, five stations. Then a maximum of ten LOP's could be plotted. Of the multiple intersections which result from plotting these ten possible LOP's along with the yet unresolved ambiguous LOP's, the fix would be determined by the one point which was passed through by all ten LOP's. Figure 7 illustrates the resulting plot using only four LOP's. This method is however, somewhat idealized since many times fixes do not reduce to sharply defined points.

At this time no decision has been made as to how far to carry the lane resolution capabilities of the Omega system. Presently, transmissions on three frequencies - 10.2, 13.6, 11 1/3 kHz -- give minimum unambiguous lane widths of 72 nmi.

e. Propagation

The dominant reason for the accuracies and coverage attainable with the Omega system is the stability of VLF propagation.

(1) Earth-Ionosphere Waveguide. At these low frequencies, the propagation can be analyzed by methods similar to those used at microwave frequencies in the analysis of waveguides. The propagation path of the VLF signal is referred to as the earth-ionosphere waveguide. Propagation in this waveguide has modes just as in conventional waveguides. This VLF signal waveguide offers propagation characteristics which favor the Omega frequency band (10 - 14 kHz). These characteristics pertain to the dominant propagation of the first order (TM_{01}) mode in the waveguide. Propagation studies, such as those



AMBIGUITY RESOULTION BY MULTIPLE INTERSECTIONS FOR 4 LOP'S

FIGURE 7

performed during the Radux tests, have shown that for frequencies below the Omega band this first order mode is attenuated more rapidly with distance from the transmitter than the Omega signal. A second characteristic is the attenuation experienced by the higher order modes generated by the Omega signal excitation of the guide. At frequencies above the 10 kHz band the higher order modes propagate with less attenuation and hence, contaminate the stable first order mode. This contamination causes poor phase stability of the received signals.

There are, however, some disadvantages in the Omega system which result from the VLF propagation path. A major difficulty is the lack of knowledge of the signal's exact propagation velocity. Studies have shown that the propagation velocity is dependent upon 1) the conductivity of the earth, 2) conductivity of the ionosphere, and 3) the height of the ionosphere.

The conductivity of the earth portion of the VLF waveguide depends upon the surface path. Consider first a path over sea water. Here the conductivity of the earth side of the guide is that of sea water. As the radio wave travels over the sea, it may encounter frozen water resulting in a change of waveguide conductivity and hence a change in propagation velocity. Other paths for the wave could be over dry, poor conductivity land, marsh lands, icy and snowy land as well as combinations of these. At each interface between different conductivity surfaces the phase velocity if the wave changes, causing a shift in the phase-difference contours of the Omega system.

(2) Diurnal Velocity Fluctuations. The conductivity and height of the ionosphere are variable and difficult to predict. Of particular interest is the diurnal fluctuations in the height of the D region ionosphere, varying from approximately 70 km daytime to 90 km at night. [3] This change in height is accompanied by a change in conductivity. These combined effects result in day-to-night variations in propagation phase velocity. For a sea water path, the daytime relative phase velocity is approximately 1.0033 and at night is 0.9995.[3] Daytime velocity factor over dry land is approximately 1.0028, while at night it reduces to 0.9995 [4] the phase shifts caused by these velocity changes take place between times of sunset and sunrise at the user and at the transmitter. Assuming the transmitter is west of the user, there will be a phase change at user sunset and another when the sun sets at the transmitter.

(3) Sudden Ionospheric Disturbances. One other type of ionospheric variation affecting the VLF propagation velocity is a Sudden Ionospheric Disturbance (SID). SID's are sudden changes in both ionospheric height and conductivity resulting from solar flares. They usually are of sufficient magnitude to render the Omega system temporarily unusable due to rapid variations in phase velocity. Fortunately, the ionosphere usually recovers from an SID after thirty minutes.

---

[3]Relative phase velocity is a ratio of the velocity of propagation, v, to the velocity of light, C. v.f. = v/c.

(4) East-West Variations. Finally, it should be mentioned that propagation east and west have different phase velocities and attenuations. This is due to the magnetic protion of the radio wave interacting with the earth's magnetic field resulting in an aiding effect west and a hindering effect east. (velocity factor = 1.0037 west versus 1.0030 east) [1]

All of these variations in propagation path characteristics affect the phase stability of the Omega transmissions and hence the system accuracy. For normal deep water navigation, the type of variations discussed here - with the exception of the SID - would be of minor importance. However, for the oceanographer, and submariner, or in a harbor approach situation, higher accuracies then those offered by the basic Omega system are mandatory. A Differential Omega mode promises to increase accuracies sufficiently so that the composite system becomes attractive to many types of special purpose users.

B. DIFFERENTIAL OMEGA

1. The Concept

a. Differential Area

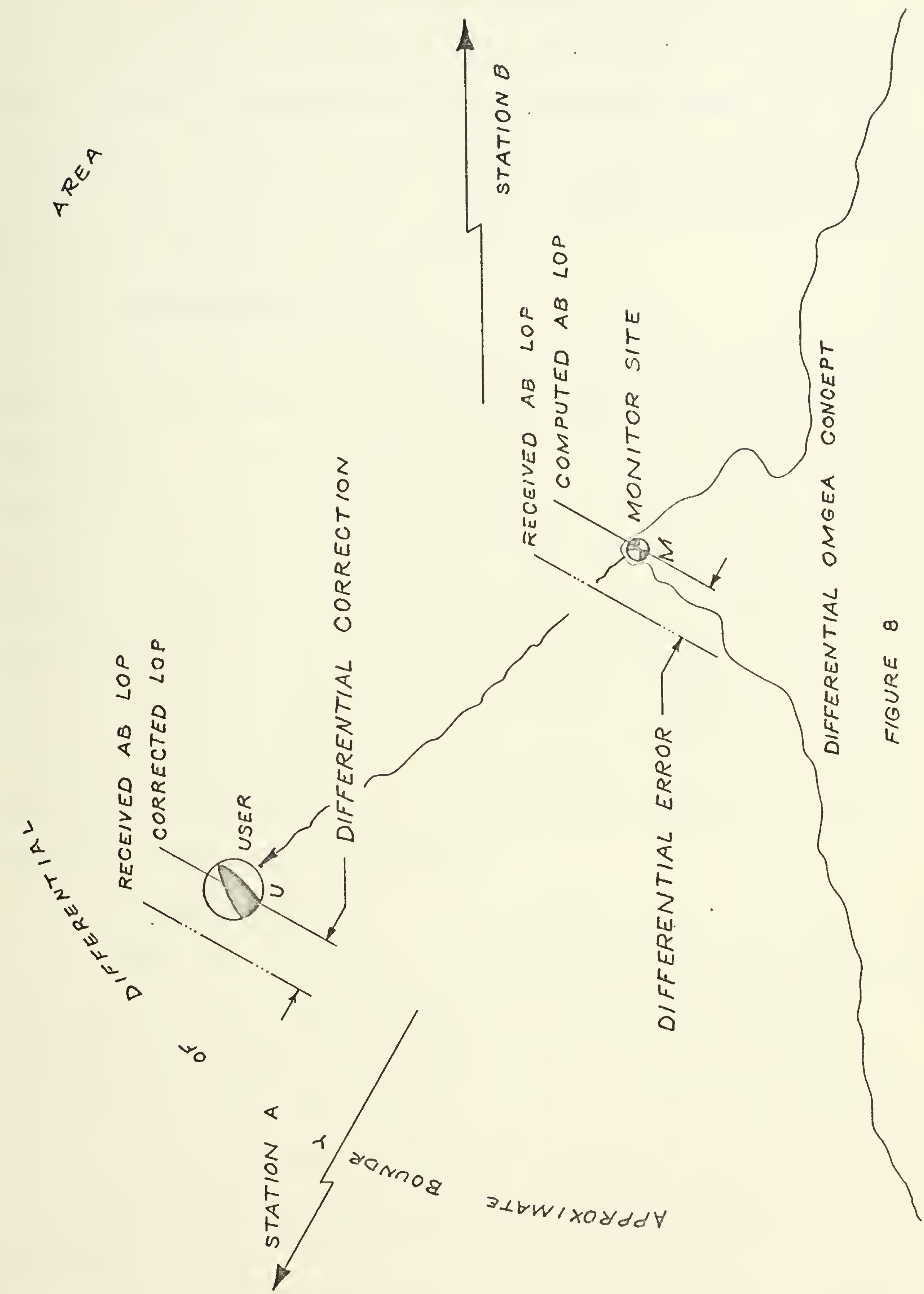
VLF transmissions experience anomalous fluctuations in propagation velocity. These variations in received times-of-arrival of Omega signals introduce navigational errors. Studies of VLF propagation conclude that these anomalies are nearly uniform over regions, called differential areas, approximately 500 nmi in diameter.

b. Monitor Sites

Omega signal anomalies affect all user receivers in the differential area to nearly identical degrees. By establishing a monitor site within this area at a known position, the degree of error introduced by propagation irregularities can be determined by comparing the monitor's known location to its perturbed Omega-fixed position. The monitor site transmits to the users in the differential area the magnitude and sense of these perturbations. Users then correct their Omega readings and thereby increase the precision of their fixes. The concept of communicating Omega propagation errors within a differential area is known as Differential Omega.

As a user travels away from the monitor site, there is an increase in the difference between anomalies experienced by his received signals and those at the monitor site. Hence, the farther a user is from the monitor, the less accurate are the corrections. Eventually, the errors in the basic Omega signals will be the same size as the errors resulting from the user's distance from the monitor station. Beyond this point, Differential Omega is of no value. For this reason, the limits of the differential area are set at a distance where the accuracy offered by the Differential Omega corrections is no better than that of the unaided Omega system. The size of a differential area is not sharply defined and may be from 100 to 300 nmi in radius.

A differential area is shown in Figure 8. Omega signals are received from stations A and B at a monitor site,



DIFFERENTIAL OMGEA CONCEPT

FIGURE 8

M, and by a user, U. These two signals are combined to determine a line of position, AB. At the monitor site, the received LOP is compared with the computed AB pair LOP. The user may be informed of the observed LOP error at the monitor, or of a fix error by adding another station pair (CD perhaps) LOP which the monitor has observed.

2. Improvements Offered

The question to be answered now is what magnitude of accuracy improvement can be obtained using the Differential Omega mode. Several studies have been conducted to test the improvements offered by, as well as the feasibility of, the Differential mode of Omega. [5,6,7,8,9] These reports have given average and r.m.s. errors ranging from 1.5 to 4.0 cec for daytime and 5.0 to 7.0 cec for nightime fixes. These figures represent an improvement over the standard Omega system of three to five times. In terms of position error, the daytime fixes gives accuracies of 200 to 1000 yds while nightime accuracies are 1500 to 2000 yds.

3. Proposed Systems

After the feasibility of a Differential mode Omega had been established, various methods of implementing such a system were proposed. Two methods make use of the high frequency (HF) band (3-30 MHz) and encode the Differential message on the carrier by some conventional form of modulation. Another method uses a Coast Guard Radiobeacon as the transmission vehicle.

a. Micro-Omega

One commercial system using the HF band is the Micro-Omega System developed by Hastings-Raydist of the Teledyne Company, Hampton, Virginia. [10] Micro-Omega utilizes a single relay station which supplements standard Omega on the lower Chesapeake Bay. The relay station transmits a single sideband audio tone whose phase contains the correction information. This system claims 300 foot accuracy (approximately 1/3 cec) as far as 200 nmi from the relay station and is fully automatic.

b. Radiobeacon System

The Coast Guard radiobeacon system, [11] referred to simply as Differential Omega, is a proposed system which is being investigated by thesis work at the Naval Postgraduate School, Monterey, California. [8] In this system, a dual carrier radiobeacon is used as the monitor and dissemination site for the correction information. The Differential information is conveyed by perturbing one of the carriers. Attainable system accuracies are being investigated through continued thesis work.

II. DIFFERENTIAL OMEGA USING A COAST GUARD RADIOBEACON

A. INITIAL SYSTEM PROPOSED BY GOODMAN

Due to the present system of Coast Guard radiobeacons in use along the coasts and in harbors of the United States, this radiobeacon is a convenient means for relaying Differential Omega information to users. Goodman proposed such a system. The attainable accuracies possible with the radiobeacon system have been investigated.

1. Possible Modulation Methods

The various schemes presented by Goodman for modulating the readiobeacon with the Differential Omega information were reviewed for possible additions or omissions. The present operational radiobeacon system uses a dual carrier type modulation system to preserve frequency spectrum. This method of modulation consists of a carrier at the beacon frequency, 307 kHz for example, which is continuous whenever the beacon is transmitting, and a second carrier displaced above the first 1020 Hz. Carrier two is keyed off and on with morse code character to identify the beacon. In this case, the second carrier frequency is 308.02 kHz. The resulting signal, when detected with a simple diode detector, appears to be an amplitude modulated signal. Besides being conservative in spectrum, this type of modulation has a continuous carrier present which can be used for radio direction finding. Some of

the various methods Goodman investigated were amplitude modulation of one of the carriers; pulse amplitude, pulse width, or pulse code modulation; frequency modulation; and carrier separation modulation. The criterion for selecting a modulation method was to disrupt the direction finding capabilities as little as possible, to use minimum frequency spectrum, and to make implementation as simple as possible.

a. Amplitude

For the amplitude modulation case, the Differential Omega message was to be proportional to the percent modulation. Since the standard radiobeacon transmitter could be easily altered to produce amplitude modulation, implementation would have been simple. This idea was discarded for two reasons. First, percent modulation is a difficult quantity to measure accurately and second, percent modulation can vary due to selective fading of the sidebands. [12] The amplitude modulation method did not offer sufficient accuracy.

b. Pulse

The various pulse modulation methods would require extensive transmitter modification. Further, the frequency spectrum characteristics for pulsed type signals would widen the frequency spectrum requirements of the radiobeacon transmitters. Another reason for rejecting the pulse modulation scheme was the requirement for complex user receiving equipment to decode the differential message.

c. Frequency

Frequency modulation was discounted primarily due to the necessity of completely redesigning the user receiver. Another disadvantage of frequency modulation is the wide spectrum required.

d. Carrier Separation

The method of carrier separation modulation consists of varying frequency of the second carrier in proportion to the Omega correction message. The result of the variable second carrier is to vary the frequency of the detected audio tone. This method would be conservative of frequency spectrum, simply detected at the user's receiver and would not alter the direction finding capabilities of the beacon. Implementation of frequency control of the variable carrier would not be simple, but it would not require excessive alteration of the transmitter.

The investigation of the possible modulation schemes led to the decision to use carrier separation modulation to encode Differential Omega messages onto the radiobeacon. The next step was to determine what information would be conveyed to the user in the Differential message.

2. Choice of Information Presented

Errors in the received Omega signal caused by propagation anomalies between transmitter and receiver appear as shifts in the station pair phase-differences. The reference differences have been calculated, or established after long periods of averaging received signals. The difference between

the reference and received phase-difference is the Differential correction. The sign of the error, referenced to the computed phase-difference determines whether the error is additive or subtractive.

There are three possible ways to interpret the phase error information collected at the Differential Omega monitor site. First the correction message is the phase error for a single station. This data would be used in conjunction with a circular grid, rho-rho, system. Second, the information is used at the site to generate a fix error which is transmitted as a Δ latitude - Δ longitude message. Third, the phase errors are derived from a two station pair LOP and this error sent to the user. Each of these ideas is discussed below.

a. Circular Grid Corrections

For rho-rho system corrections the observed off-set of the monitor received circular LOP is transmitted to the user who corrects his LOP. One main disadvantage of the rho-rho Differential system, and with the circular gird system generally, is the requirement for an on-board stable oscillator used for tracking the received phase of the single transmitting station. Another problem with this system is the non-availability of circular grid Omega Charts.

b. Δ latitude - Δ longitude Corrections

To develop the correction information for the Δ latitude - Δ longitude scheme, it is necessary to compute a navigational fix at the monitor site using either radial lines of position or station pair LOP's. Then, the received fix is compared to the true monitor site fix. This requires that

each fix be divided into north-south and east-west components. An error message can be formed by combining the errors in both longitude and latitude. Although such a correction might be favorable to a navigator, the monitor site would require some form of a special purpose computer to calculate the components of the received fix and then compute the errors.

c. Line of Position (LOP) Corrections

The error correction can be in the form of station pair LOP adjustments. This message is similar to the radial LOP message. Instead of a single station, the receiver compares the received phase of two Omega transmitters and computes a relative phase-difference. The resultant received phase-difference LOP is compared to the computed one. The error is transmitted to the user who then corrects his received LOP. Since the Omega system is intended to be used in a station pair configuration, only a moderately stable oscillator - which may be a part of the receiver - is required and Omega navigation charts are published with hyperbolic pair information plotted.

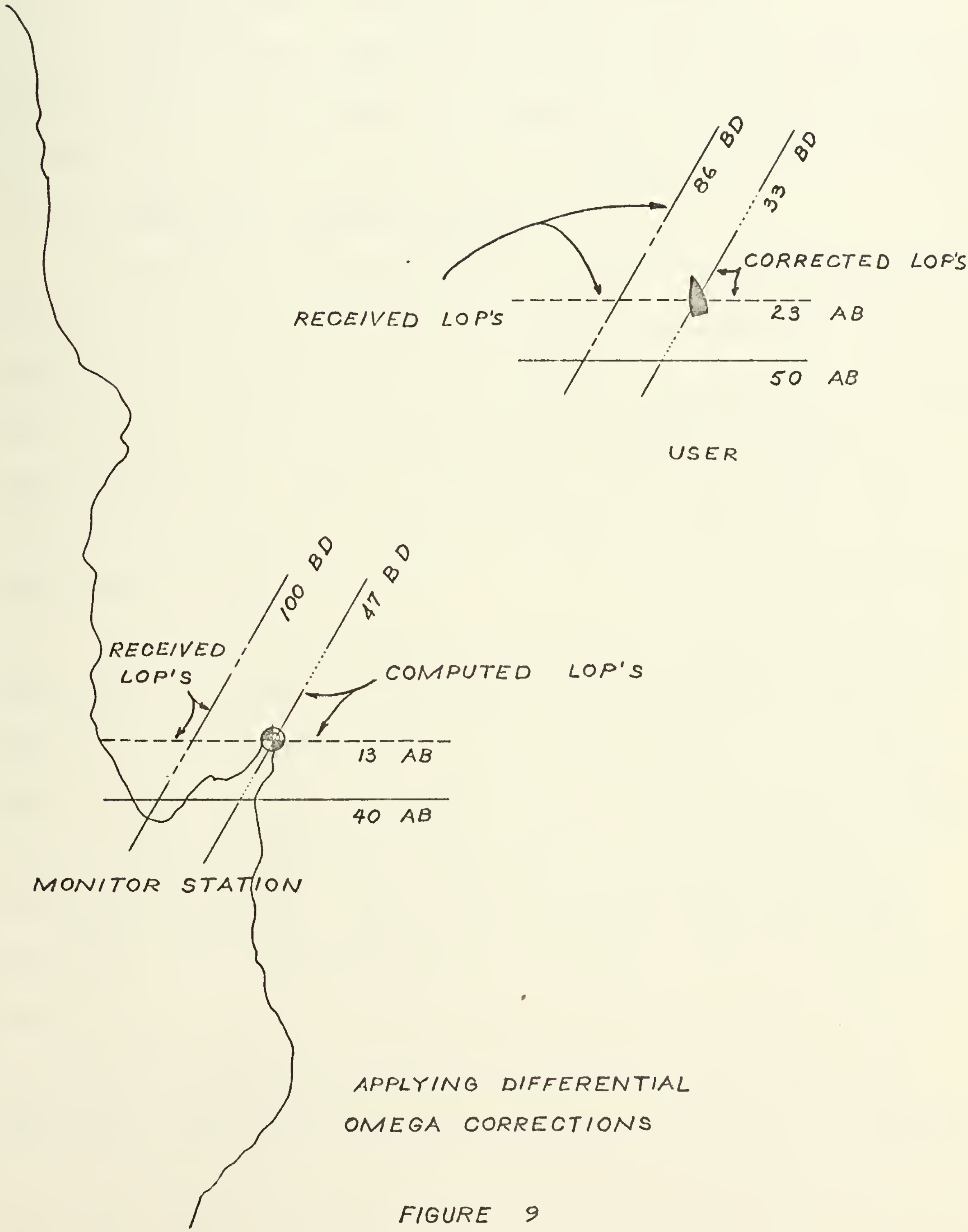
Figure 9 illustrates the method of applying the correction information. In this example the monitor has computed his AB LOP to be 13.0 cec and his BD line 47.0 cec. His received signals at this instant are 40.2 cec and 100.0 cec respectively. To compute the Differential correction, the received phase is referenced to the calculated phase.

error = reference LOP - received LOP

error AB = 13.0 - 40.2 = - 27.2 cec

error BD = 47.0 - 100.0 = + 47.0 cec

	MONITOR STATION CALCULATED LOP	RECEIVED LOP	CORRECTION
AB	13 CEC	40 CEC	-27 CEC
BD	47 CEC	100 CEC	+47 CEC



APPLYING DIFFERENTIAL OMEGA CORRECTIONS

FIGURE 9

These errors are transmitted to the user whose received LOP's are AB, 50.0 cec and BD, 86.0 cec. To find the actual LOP, the user adds the correction to his reading:

true LOP = received LOP + LOP correction

true LOP AB = 50.0 + (-27.2) = 22.8 cec

true LOP BD = 86.0 + 47.0 cec = 133.0 cec = 33.0 cec

Notice in the true BD LOP, the result gives a phase reading of 133.0 cec which is the same as 33.0 cec.

3. Modulation Scheme Selected

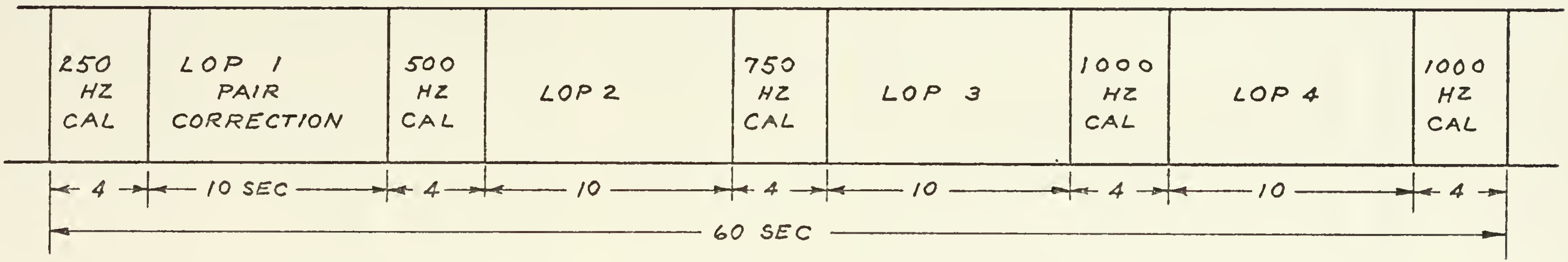
Following the investigation of the possible modulation schemes, and selection of the correction information best suited to the general user, the form of the correction message was reviewed. Points considered were message reliability, understandability, ease of decoding, and ease of adapting to either manual, semi, or fully automatic Differential Omega receiving systems.

One of the primary constraints on Goodman's work was the requirement to modify the existing Coast Guard Radiobeacon system as little as possible. For this reason, the suggested signal format was designed to be transmitted in a sixty second interval which is the time given each beacon operating on a particular frequency. Usually five beacons share the same frequency, each transmitting for one minute of a five minute cycle.

The Differential Omega message proposed contained correction information for four station pair LOP's. Although

only two LOP corrections are needed to adjust a fix, most navigators would prefer a third correction as a check. Four corrections, offer sufficient redundancy to allow for Omega transmitter malfunctions without dangerous system degradation. Between each correction segment was a calibration period which could be used by the navigator as a check of his receiving and decoding equipment. Calibration segments were four seconds long and Differential messages ten seconds long. The received message consisted of a continuous audio tone whose frequency was proportional to the magnitude of the LOP error (Figure 10). Calibration tones separated Differential LOP's. Since the Differential error could be either positive or negative, the message had to convey the sense as well as the magnitude of the error.

The next step in the formulation of the message format was to determine the magnitude range of errors which would be encountered under typical operating conditions. From data collected in the various Differential Omega feasibility studies and his own experiments, Goodman concluded that LOP error limits ± 50 cec were sufficient. With the standard radiobeacon modulating frequency of 1020 Hz, an upper limit of 1100 Hz was chosen for the + 50 cec error case. The span of corrections totaled 100 cec. Assuming a receiver low frequency audio cutoff near 100 Hz, this was set as the -50 cec error giving a total frequency range of 1000 Hz with a mid range of 600 Hz corresponding to zero error. The resultant scale factor



DIFFERENTIAL OMEGA CORRECTION MESSAGE FORMAT PROPOSED
BY GOODMAN

FIGURE 10

is 1.0 cec = 10 Hz. Calibration frequencies of 250, 500, 750, and 1000 Hz were selected. The complete message format is shown in Figure 10.

4. Block Diagram of Proposed System

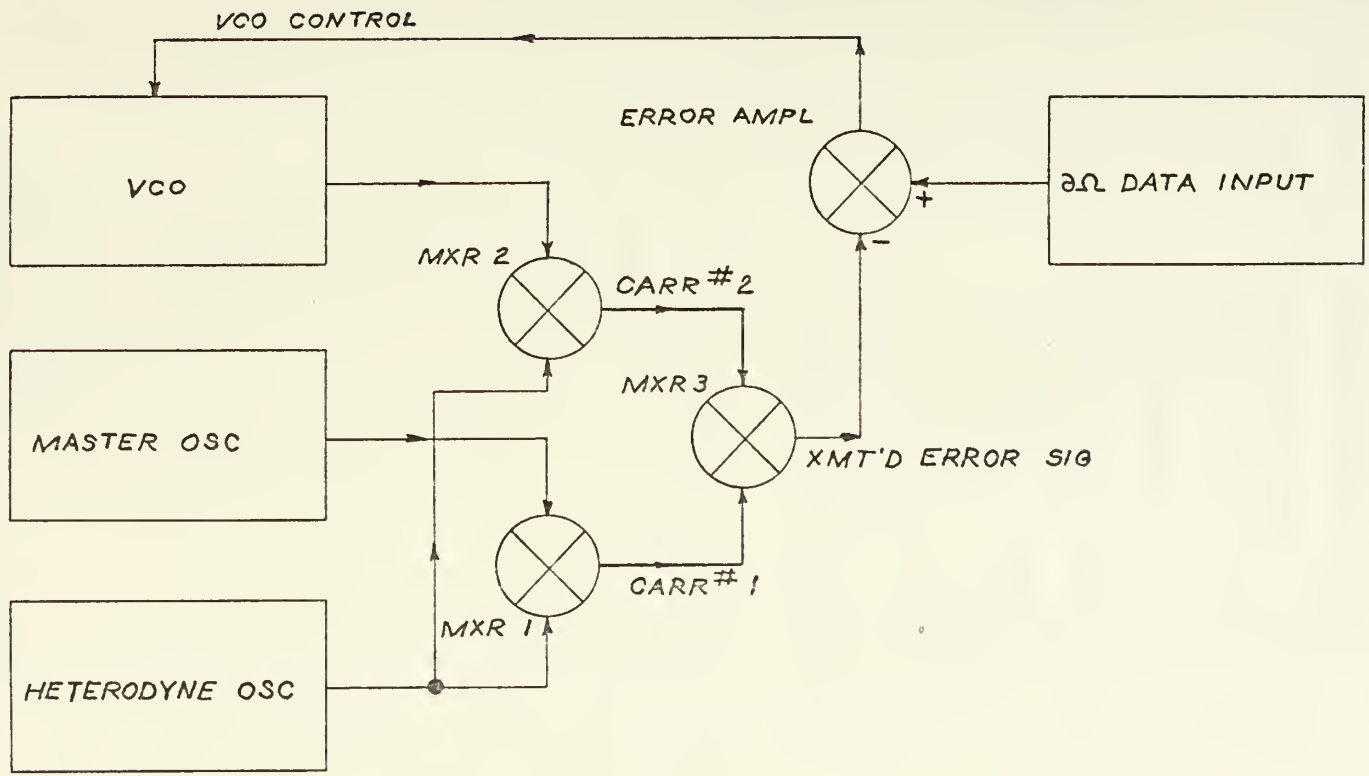
Goodman's proposed system block diagram for the Differential Omega transmitter-monitor site is given in Figure 11. The frequencies of the two radiobeacon carriers are generated by mixing the output of heterodyne oscillators. The second carrier offset is locked to the desired frequency by a closed feedback loop to the voltage controlled oscillator (VCO). The idea of using heterodyne oscillators was developed because each Differential Omega transmitter installed would require calibration and alignment. Unless all these Differential beacons operated at the same frequency, the characteristics of the VCO and feedback loop would be different for each new frequency. With heterodyne oscillators, the frequency control would be fixed and only a new crystal would be needed to change frequency.

The voltage control feedback loop receives inputs from the Omega comparitor which compares the received and calculated LOP's. This input to the loop sets the VCO frequency and the resulting second carrier or modulating frequency.

The carrier separation scheme was used for the system analysis.

B. ANALYSIS OF GOODMAN'S SYSTEM WITH SUGGESTED IMPROVEMENTS

After completing the review of the Differential system proposed by Goodman, various portions of the system were



BLOCK DIAGRAM OF RADIOBEACON TRANSMITTER MODIFICATIONS

FIGURE 11

analyzed from the viewpoint of attainable accuracy, design philosophy, usability, and system reliability.

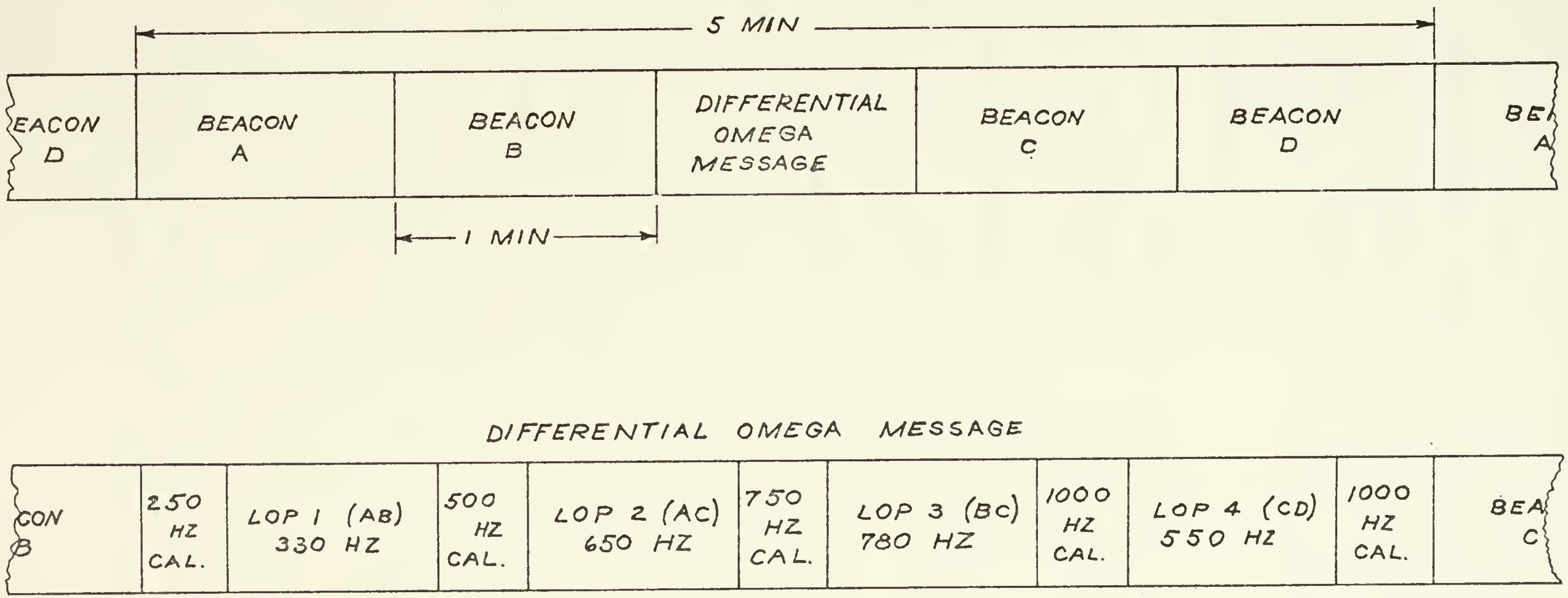
1. Correction Message Coding Method

The proposed message format is easily generated and offers to the user frequent calibration tones. Points which seem troublesome are the uncertainty in the decoding process resulting from human error or system interference and the necessity of using correction information on a non real-time basis. The latter refers to the transmission of correction information one minute out of every five. This is considered to be a flaw in the system implementation philosophy and will be investigated later.

The decoding uncertainty arises because the various LOP correction segments are identified only by their relative position in the message group. Figure 10 shows the message format; Figure 12 gives a simulated message. Observe that no hesitations separate the calibration tones from the message tones. It is possible that a noise burst or some system interruption could mask one of the calibration tones or a part of a correction message and cause confusion. The user would then be forced to wait five minutes before the question could be resolved.

a. Goodman's Format

The analysis of the correction message format consisted of playing magnetic tape recordings of simulated correction messages to student subjects and then analyzing their reactions to the test. The audio output of the tape



SIMULATED CORRECTION MESSAGE

FIGURE 12

recording was fed to an analog frequency meter which indicated the frequency of the tones. Subjects were encouraged to make comments on the message format. Two tests tapes of each format were used. One was a "strong signal" message in which receiver noise was negligable; the other was a more realistic message recorded with receiver noise to simulate typical receiving conditions.

Figure 12 shows the test tape layout used to evaluate Goodman's proposed message format. The recording contained three complete cycles of a five radiobeacon group which presented three different sets of Omega corrections. This allowed the subjects to become more familiar with the format as the test progressed.

Most subjects understood the LOP correction message after hearing the first group. All subjects were given a diagram similar to Figure 12 explaining the message format. Most found the best method to collect LOP corrections was to record all the frequencies received and then eliminate the calibrations tones after the Differential Omega segment was finished. An opinion expressed by the subjects was that they would have preferred some form of LOP identification. All subjects felt that the ten second interval was ample to read and record the LOP correction reading.

b. Addition of LOP Identifications

A second message format tape was generated which placed an identifier immediately before the LOP signal. The

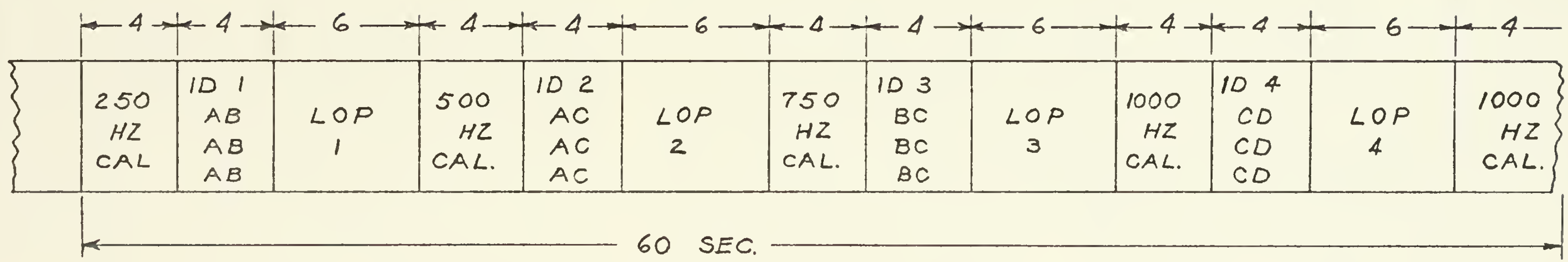
identification consisted of the morse code letters for the Omega station pair (for instance, AD) sent rapidly three times. The ten second correction interval used previously was divided into two parts; the first four seconds were used to identify the station pair, and the remaining six seconds contained the continuous tone representing the correction signal. The radiobeacon segment of both tapes was the same. Figure 13 shows the signal format for this second test.

Student comments on this format indicated that the LOP identification left no doubt as to when the LOP correction had begun or which LOP was being received. It was observed, however, that only six seconds for reading the meter scale, as compared to the ten seconds on the first tape, was not sufficient. Most felt a longer time would be more desirable allowing time for a second glance.

The average reading error for all subjects tested tapes was 4 Hz with the mean deviation at 2.3 Hz. These numbers are in agreement with normally accepted accuracies obtainable with the meter used whose smallest increments were ten Hz.

c. Time Frame Calculations

Before making a final message format recording, calculations were carried out to determine how often Differential Omega information is required in a harbor approach situation. Since correction information is available once every five minutes, the amount of change in Omega readings accumulating in this time must be found. Assuming the onset



CORRECTION MESSAGE WITH LOP IDENTIFICATION

FIGURE 13

of an average solar flare occurs at the end of a correction message, the possible change in Omega readings would be [13]

$$160° \text{ phase shift}/40 \text{ minutes} = 4°/\text{min}$$

$$4° = 0.9 \text{ cec}$$

$$4° = 270 \text{ yds/min} = 1350 \text{ yds}/5 \text{ min}$$

or nearly 3/4 nmi error which is four times the tolerable limit. To solve this problem, more frequent Omega corrections must be transmitted. One complete correction message per minute was found to be the maximum data rate.

d. Final Message Format

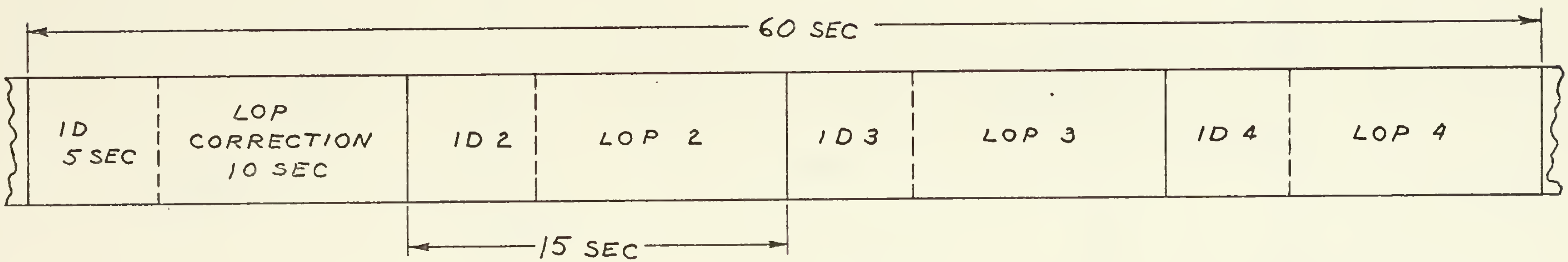
The findings of the preceeding message formats aided in formulating the final tape recording. Four LOP corrections are transmitted in a one minute interval. Station pair identifications are transmitted for five seconds before each ten second LOP correction tone. The entire message repeats every minute. Figure 14 shows the final message format.

2. Transmission Method

Tests were performed to determine the frequency controllability of the transmitted carriers. A mock-up of the radiobeacon transmitter modifications was constructed for use in these tests. The effects of oscillator drifts were analyzed for two systems. The proposed modulation circuitry was evaluated and a second one was tested which was capable of being set by a digital command.

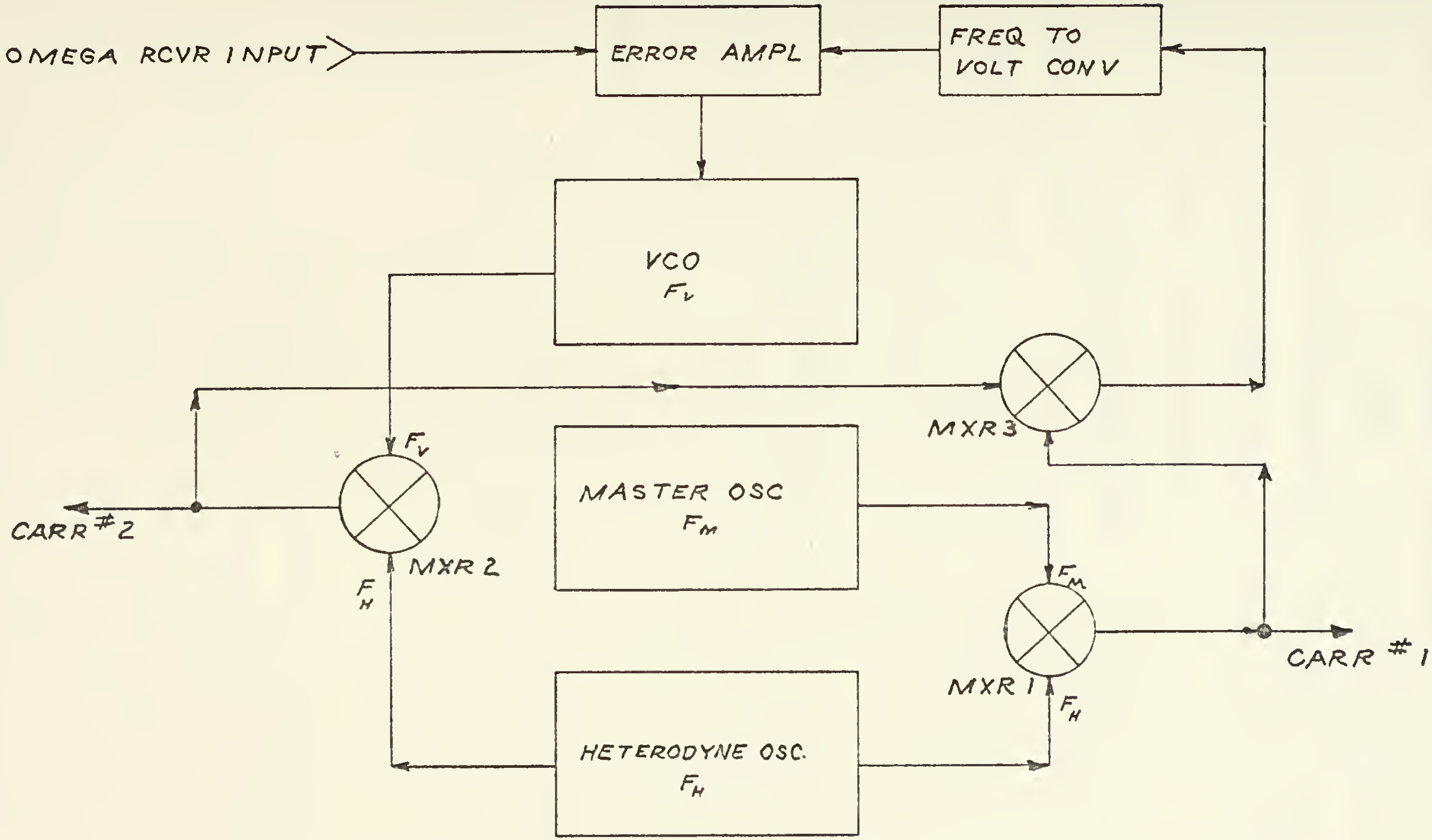
a. Oscillator Drift Errors

Using the test circuitry connected as in Figure 15, calculations were made to determine the magnitude of errors



FINAL MESSAGE FORMAT

FIGURE 14



RADIOBEACON TRANSMITTER MODIFICATION TEST CIRCUITRY

FIGURE 15

resulting from oscillator drifts of one part in 10^7. The radiobeacon frequency used was 307 kHz. Required oscillator frequencies were, 1) master oscillator, 4.000 MHz, 2) heterodyne oscillator, 3.697 MHz, 3) VCO, 4.000600 MHz plus or minus the Differential correction. Carrier number one was 307 kHz and carrier number two was nominally 307.6 kHz (600 Hz tone represents zero error).

(1) Master Oscillator. Assuming the master oscillator had drifted to its tolerance limit, 4000.0004 kHz, the VCO would be offset by the error voltage an equal amount and the resultant detected modulation would be correct. Positive or negative drifts had the same effect.

(2) Heterodyne Oscillator. A similar maximum tolerance error was assumed for this oscillator. The resulting system error was corrected by offsetting the VCO until the detected signal was on frequency.

(3) Simultaneous Drift of Both Oscillators. For the case of both oscillators simultaneously off frequency, the error amplifier caused the VCO to move until the output was correct.

The above calculations assumed the feedback loop was functioning properly. Possible errors could result from component drifts or power fluctuations which might cause offsets in the frequency correcting function of this loop. As a means of eliminating errors from feedback loop malfunctions another method of carrier generation was reviewed.

b. Partially Synthesized Oscillator Drift

This carrier generation method used a frequency synthesizer in place of Goodman's VCO and feedback loop. No feedback arrangement checked the output. Figure 16 shows a block diagram of this modulation circuitry.

(1) Master Oscillator. If the master oscillator was allowed to drift to the tolerance limit (0.4 Hz error), the detected frequency was in error by the same amount and in the same direction.

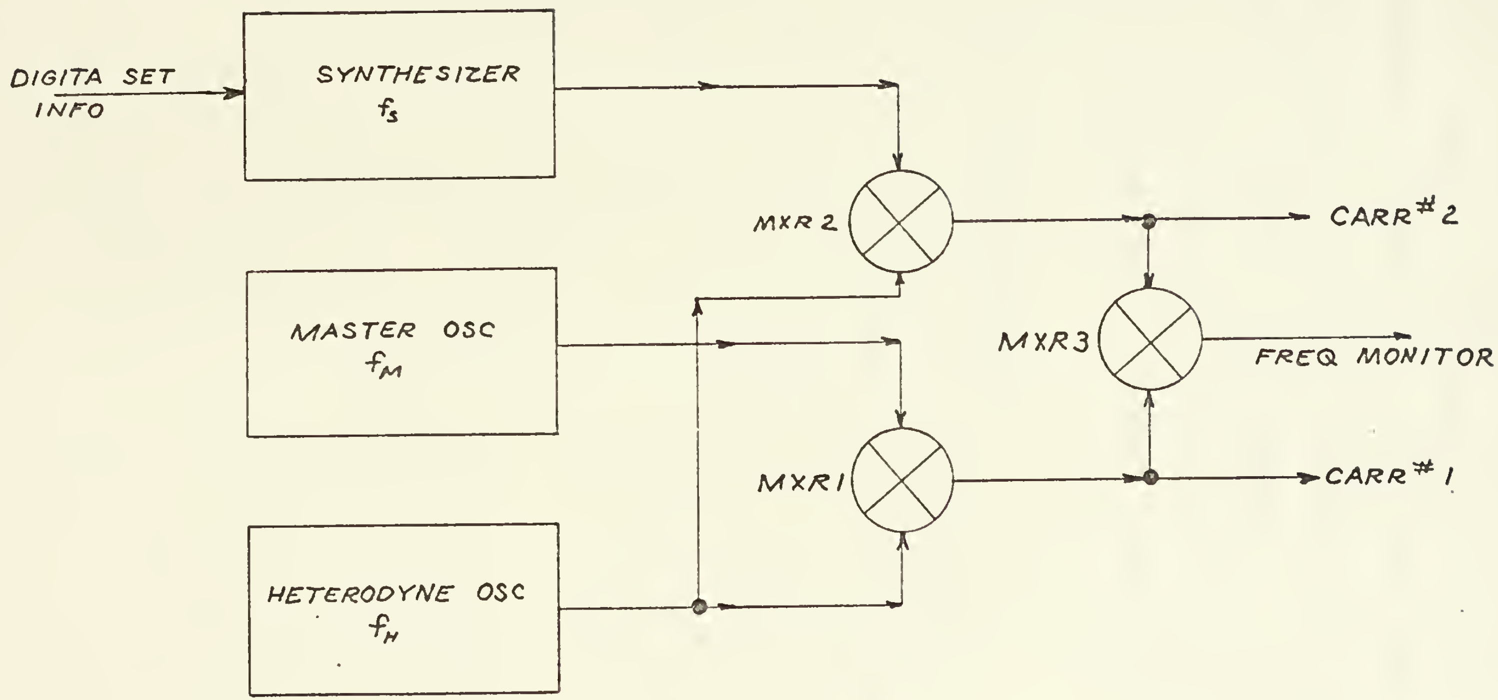
(2) Heterodyne Oscillator. Since this oscillator was used to generate both carriers, the output error for a tolerance limit drift was twice the oscillator error.

(3) Simultaneous Drift. For this case, the resulting error was the greater of the two offsets and in the same direction.

Other errors were discovered in the laboratory tests of this system. Offsets between various oscillators in the modulation circuits and test instruments demonstrated how various drifts interact. To resolve the multiple oscillator control problems discovered in the experiments, a third frequency control method was conceived.

c. Fully Synthesized Frequency Control Method

Observations previously mentioned led to the proposal of a completely synthesized frequency control scheme. This method is capable of eliminating offset, between the system frequencies and incorporating a frequency correcting feedback loop. Instead of several independent crystal



PARTIALLY SYNTHESIZED FREQUENCY GENERATION

FIGURE 16

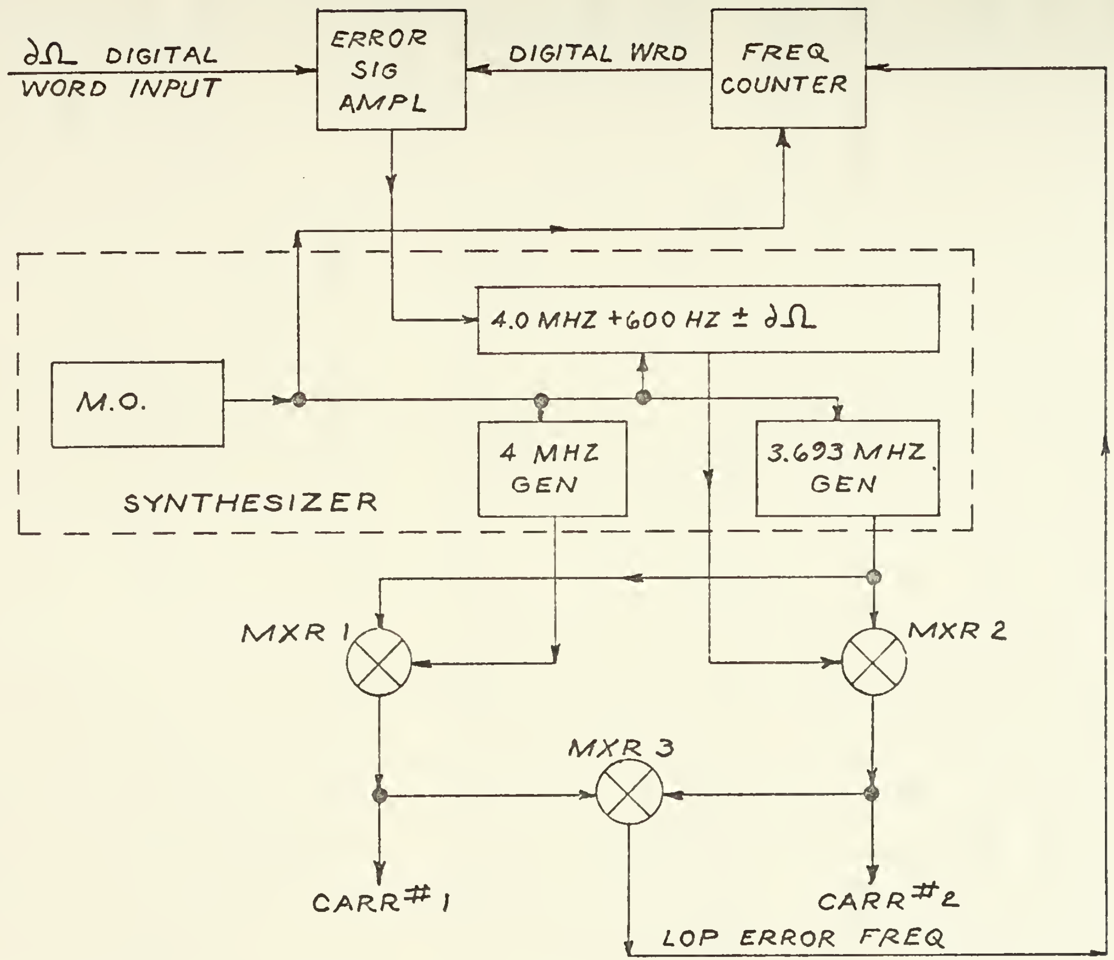
oscillators in the transmitting equipment and the Omega receiver, a single high stability oscillator controls the entire system. Radiobeacon carriers are generated within the frequency synthesis process while the Differential Omega information is endoded by digital word commands. A frequency counter controlled from the master oscillator serves as the feedback convertor and error detector. A block diagram of this scheme is shown in Figure 17.

3. <u>Receiving Station Analysis</u>

As the final step in the system analysis, the receiving portion of the Differential Omega system was reviewed. The Differential Omega receiver consists of a conventional radiobeacon receiver and an audio frequency indicator. Two different types of frequency measuring instruments were considered, an analog frequency meter and a digital frequency counter.

a. Analog Frequency Meter

Hewlett Packard models 500 BR and 5210 A/B frequency meters were tested. These meters indicated from zero to 1000 Hz on the ranges used with smallest scale increments of 10 Hz. The manufacturer specifies accuracies of 1.0 percent of full scale in the normal mode and 0.2 percent for expanded scale operation. [14] Converting to centicycles, this accuracy represents navigational tolerances of $\pm$ 1.0 cec ($\pm$ 300 meters) or $\pm$ 0.2 cec ($\pm$ 60 meters). For operational ease, the meter face was relabeled to read directly in centicycles with a zero center. Difficulty was experienced with the expanded scale feature of the analog meters. The operator movements



FULLY SYNTHESIZED MASTER OSCILLATOR CONTROLLED TRANSMITTER BLOCK DIAGRAM

FIGURE 17

required to change scales consumed nearly ten seconds leaving no time to read the meter. Also, since an additional set of scale graduations is required, the possibility of operator confusion exists.

b. Digital Counter Readout

The frequency counter was connected to the radiobeacon receiver exactly as the analog meter. Using a one second gate in the counter, the finest resolution is 1.0 Hz. Precision of the counter is always the observed reading plus or minus one count. [15] In this case, plus or minus one count represents $\pm$ 1.0 Hz, corresponding to a navigational uncertainty of $\pm$ 30 meters.

With input changes of 1.0 Hz, the counter indicated frequency to within the expected one count ambiguity. One disadvantage of a digital counter readout is the requirement to convert frequency readings to centicycle corrections. In an operational system, this conversion would be simply performed electrically.

c. Master Oscillator Receiving System

A Differential Omega user must have an Omega receiver with its own stable internal oscillator and a radiobeacon with its associated frequency indicator. Since a stable oscillator is a necessary part of the system, it could be used as an external clock for the digital counter in addition to its normal receiver function. In this way, frequency offsets resulting from counter clock errors are reduced.

d. Calibration Requirements

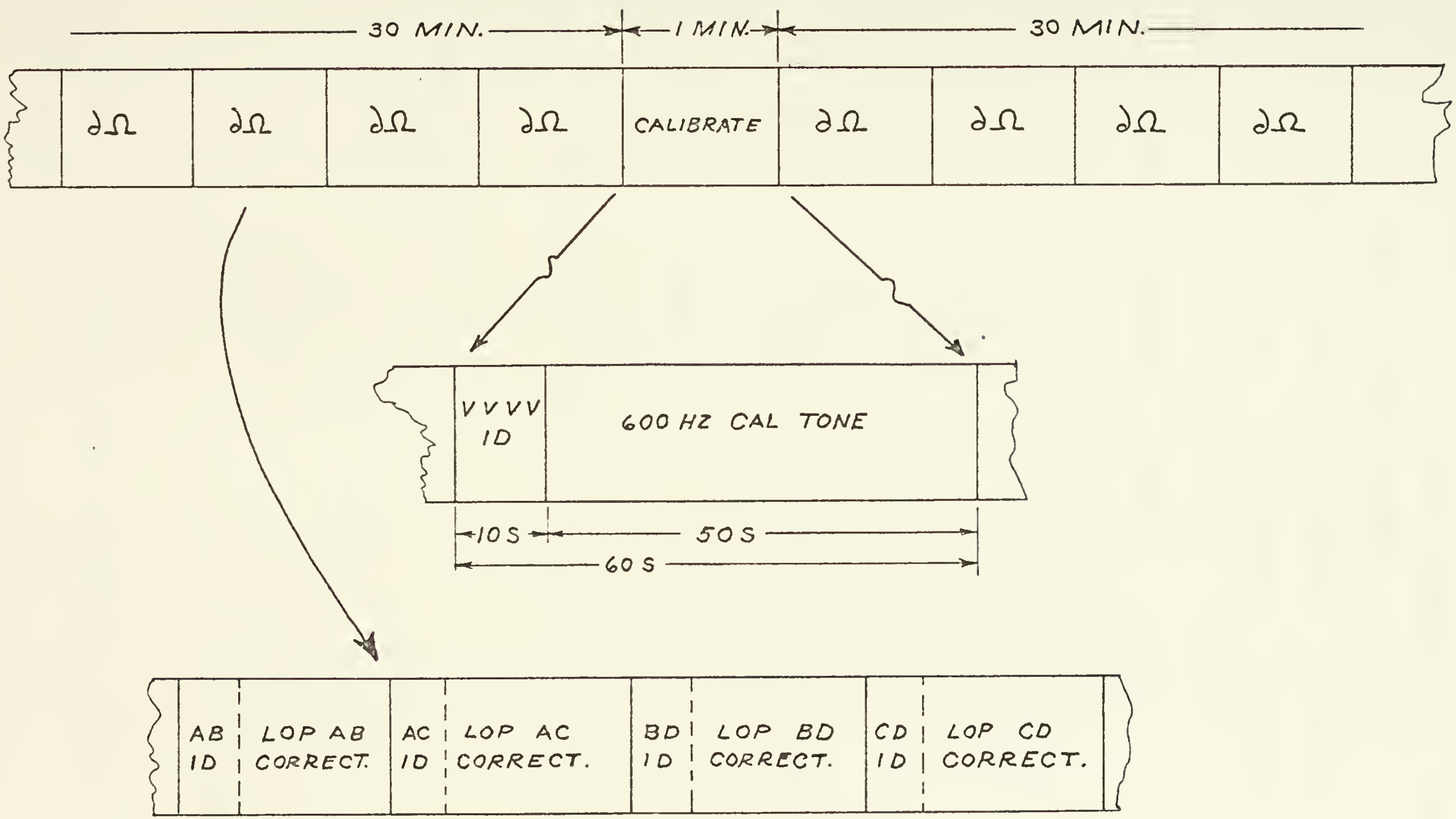
For the two readout schemes tested, the calibration requirements were vastly different. The analog frequency meter must be recalibrated every 30 minutes because of the circuitry it contains. Most digital frequency counters do not need field calibration. However, frequency errors do result from fixed offsets in the counter clock. These offsets can be eliminated by using a more stable external oscillator if available.

Because of the no-calibration feature of the master oscillator receiver arrangement, and the 30 minute calibration span for the analog meter, calibration tones were eliminated from each one minute segment of the Differential Omega message format. In their place, a 60 sec calibration tone was transmitted at 30 minute intervals. This is shown in Figure 18.

The most desirable receiver system is, thus, the digital counter readout with electronic scaling to give direct centicycle corrections. The Omega receiver internal oscialator drives the counter. Thirty yard accuracy can be obtained using a one second count gate.

C. THE MASTER OSCILLATOR CONTROLLED DIFFERENTIAL OMEGA SYSTEM

The result of the analysis of Goodman's system with the proposed changes is the master oscillator controlled Differential Omega system. This system features digital readout and frequency synthesized signal generation.



CORRECTION MESSAGE FORMAT WITH CALIBRATION SEGMENT

FIGURE 18

1. Transmitter

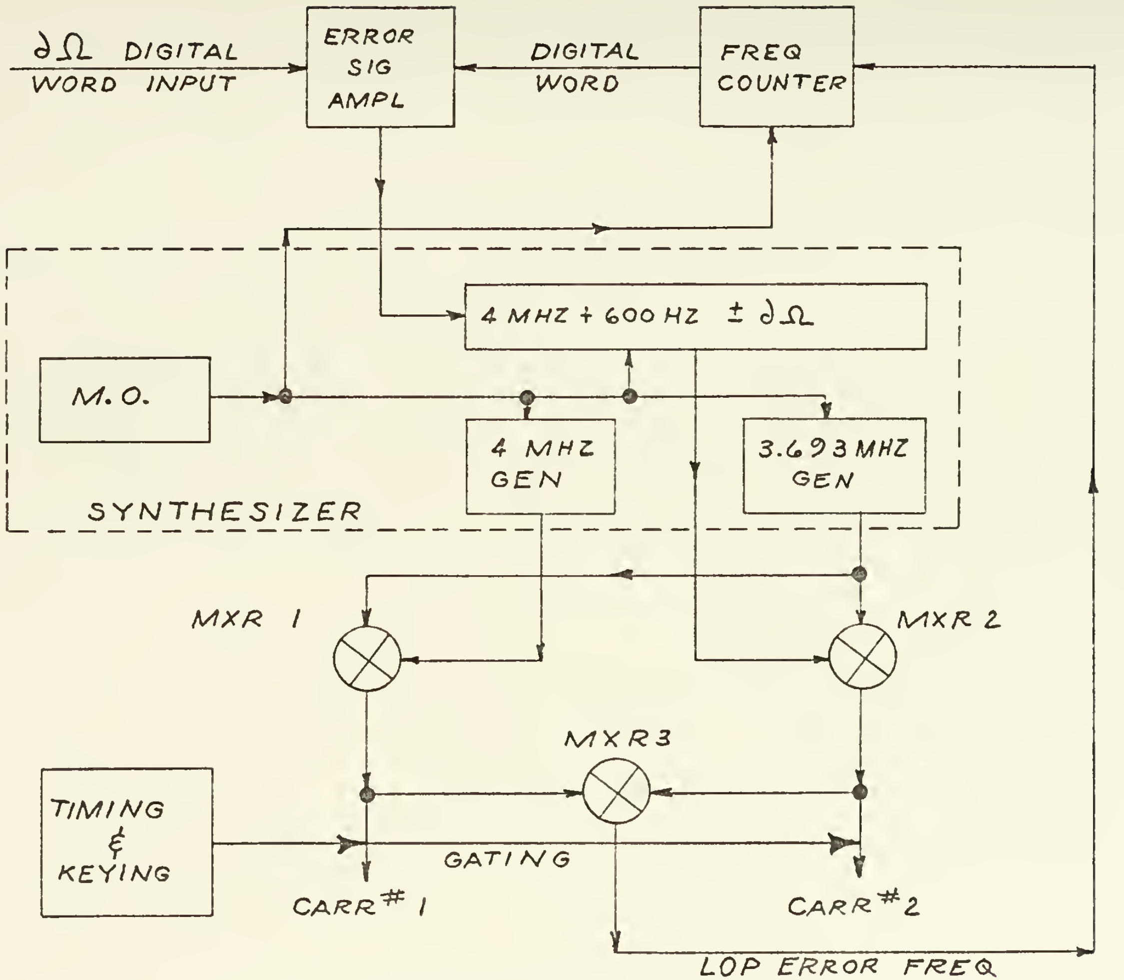
The dual carrier Coast Guard radiobeacon transmitter is controlled by a highly stable master oscillator. Figure 19 is a block diagram showing the frequency synthesizer which consists of three main parts. Two wired-in circuits generate the frequencies used to produce carrier number one. Carrier number two, whose programmable frequency conveys the Differential Omega message, is generated from one of the wired-in frequencies and the digitally controlled synthesized frequency which in turn is determined by the Differential error. As a check on the system, a frequency counter is used in an error correcting feedback loop.

The Differential Omega information is transmitted according to the message format shown in Figure 18. The timing and keying blocks of Figure 19 determine the message intervals.

The master oscillator system eliminates oscillator drift errors, and results in navigational accuracies of better than 30 yds.

2. Receiving System

The master oscillator controlled receiver is designed to give high accuracy and simple operation. Using the Omega receiver internal oscillator to drive the frequency counter readout eliminates another free-running oscillator from the system. The no-calibration feature of the counter creates user confidence in the system, and electronic scaling displays direct LOP corrections.



MASTER OSCILLATOR CONTROLLED DIFFERENTIAL OMEGA TRANSMITTING SCHEME

FIGURE 19

For a completely automated, receiving system, digital corrections are easily applied to readout displays. The increased information rate of the message format offers continuous corrections of Omega information.

III. CONCLUSIONS AND RECOMMENDATIONS

Omega is a world-wide VLF navigation system capable of one to three mile accuracy. Propagation variations cause system errors, however, within small differential areas, these anomalies may be considered uniform. Differential Omega is the process of observing propagation fluctuations and disseminating navigation correction information to users in the differential area. In this way improved accuracies up to five times that of the Omega system are possible.

The use of a Coast Guard radiobeacon has been suggested as a communication link for Differential Omega information. Goodman proposed a system to encode corrections on the beacon transmissions. His system was reviewed and improvements were suggested.

The correction information presented to the user is LOP corrections. This form of correction is simply generated and may be encoded on the radiobeacon transmissions with moderate modifications to the existing equipment. To use the correction information, the navigator merely adds the correction, algebraically, to his received LOP.

The format of the Differential Omega message must contain some method of identifying each LOP correction. A simple identification is to transmit the LOP station pair name (for example, AB) in international morse code prior to that Differential message. The use of digital readout equipment at

the Differential system was analyzed to determine its own precision. The next major step in an overall system investigation is incorporating the receiver and determining a practically attainable overall accuracy.

Before including the Omega receiver in the Differential system, tests must be conducted to specify receiver limitations. Points of interest include the reliability of weak signal comparisons, introduction of phase errors due to restricted dynamic range of receiver circuits - phase detectors, comparitors, integrators - and optimum integration time constants. The required precision of the received Omega LOP, for use with the Differential system, must be established.

After determining if the present Omega receivers are acceptable for use in a Differential mode, an actual test system should be implemented using the radiobeacon scheme presented here. Performance can be evaluated and compared with operation systems from both electronic accuracy and user acceptability viewpoints.

Although the bulk of these investigations were oriented to nautical situations, the possibility of airborne usage should be considered.

Finally, all Differential Omega systems which have been investigated should be compared to determine which one is most practical for installation in major harbors.

the receiver eliminates the requirement for instrument calibration. The analog frequency meters tested required calibration at approximately 30 minute intervals, thus, a single calibration tone is transmitted for one minute each half hour to accommodate users who prefer this type readouts. Calculations demonstrated that during a five minute interval Omega readings could change a position fix by 3/4 nmi which is approximately four times the acceptable error. Differential Omega corrections should therefore be transmitted at one minute intervals. The proposed Differential Omega message format is shown in Figure 18.

The frequency generating scheme initially proposed was subject to errors caused by oscillator drifts and feedback circuitry malfunctions. To eliminate such errors, a master oscillator controlled frequency generating method was proposed which features frequency synthesis and digital control. With this system, the Omega corrections are controlled to 0.1 Hz.

The receiving portion of the system reads LOP corrections directly from a frequency counter employing electronic scaling. The counter uses as its driving source the Omega receiver internal oscillator. Received LOP corrections of 1.0 Hz or 0.1 cec could be detected.

The entire master oscillator controlled system used digital control and is capable of better than 30 yd navigational accuracies.

All of the analysis and testing of this Differential scheme was performed independent of an Omega receiver. In this way,

BIBLIOGRAPHY

1. Pierce, J. A., and others, Omega, A World-Wide Navigational System, 2d ed., DDC no. AD-630 900, 1966.

2. Naval Electronics Laboratory Center Report 1153, Technical Evaluation of Omega Navigation System, by the Omega System Group, 18 December 1962.

3. Watt, A. D., VLF Radio Engineering, Pergamon Press, 1967.

4. Naval Electronics Laboratory Center Report 1185, Accuracy of the Omega Navigation System, by M. L. Tibbals and D. P. Heritage, 2 October 1963.

5. Naval Research Laboratory Memorandum Report 1573, Rendezvous Accuracy of the Omega Navigation System, by J. W. Brogden, A. N. Duckworth, and J. J. O'Neill, 17 November 1964.

6. Naval Research Laboratory Memorandum Report 1716, Differential Omega, by J. W. Brogden and K. O. L. Luken, 8 August 1966.

7. Tracor, Inc. Report 67-135-U, Final Technical Report, Differential Omega Test and Evaluation Program, 18 January 1967.

8. Goodman, G. R., A Proposed Differential Omega System, M.S.E.E. Thesis, Naval Postgraduate School, Monterey, California, 1969

9. Scientific Management Associates, Inc., Report NObsr - 95105, Differential Omega Feasibility Test, January 1967.

10. Hastings-Raydist, A Teledyne Company, TN-20A, Micro-Omega, 300 Foot Accuracy and World-Wide Coverage from a Single System, March 1970.

11. Swanson, E. R. and Davis, W. E., System and Method for Operating Medium Accuracy Navigation, U.S. Patent 3,161,880, 15 December 1964.

12. Terman, E. E., Electronics and Radio Engineering, 4th ed., McGraw-Hill, 1955.

13. Central Radio Propagation Laboratory, National Bureau of Standards, NBS Course in Radio Propagation, Ionosphere Propagation, Lecture No. 11, VLF Propagation-II, by A. G. Jean, Summer 1961.

14. Hewlett Packard Technical Data, Frequency Meter and FM Discriminator model 5210 A/B, 1 April 1967.

15. Doyle, J. M., Pulse Fundamentals, Prentice-Hall, Inc., 1964.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documenation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Commandant U.S. Coast Guard NASSIF Building 400 Seventh Street, S. W. Washington, D. C. 20591	1
4.	Professor C. E. Menneken, Code 023 Dean of Research Naval Postgraduate School Monterey, California 93940	5
5.	Assistant Professor R. W. Adler, Code 52Ab Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940	1
6.	CDR R. H. Baetsen, Jr. Commandant, U. S. Coast Guard NASSIF Building 400 Seventh Street, S. W. Washington, D. C. 20591	1
7.	Commanding Officer U. S. Coast Guard Electronics Engineering Center Wildwood, New Jersey 08260	2
8.	LT M. E. McKaughan, USCG Electronics Engineering Center Wildwood, New Jersey 08260	1

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

RIGINATING ACTIVITY (Corporate author) aval Postgraduate School onterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

EPORT TITLE

nalysis of a Proposed Differential Omega System

ESCRIPTIVE NOTES (Type of report and, inclusive dates)

aster's Thesis; December 1970

UTHOR(S) (First name, middle initial, last name)

ichael Eugene McKaughan

EPORT DATE ecember 1970	7a. TOTAL NO. OF PAGES 71	7b. NO. OF REFS 15
CONTRACT OR GRANT NO. PROJECT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

DISTRIBUTION STATEMENT

his document has been approved for public release and sale; its istribution is unlimited.

SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Postgraduate School Monterey, California 93940

ABSTRACT

Omega, a world-wide, VLF, CW, all-weather navigation system offers ne mile resolution, but suffers in accuracy due to propagation nomalies which have been found to be relatively constant over dif- erential areas. Differential Omega is the process of disseminating ropagation-produced error to users in the differential area. Accuracy mprovements of 5 to 1 are possible.

A system of Differential Omega using a Coast Guard Radiobeacon as proposed by Goodman. His system has been reviewed and improvements uggested. The correction message format was reviewed and changed to nclude line of position (LOP) identification. A revised transmitting cheme using a master oscillator controlled frequency synthesis process ith digital readout is evaluated. Using the frequency synthesized aster oscillator controlled Differential Omega system, accuracies of 0 yards can be realized for idealized Omega receiver inputs.

D FORM 1 NOV 65 1473 (PAGE 1)

/N 0101-807-6811

Security Classification

A-31408

Security Classification

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
ega						
perbolic Navigation						
iobeacons						
ctromagnetic Radiation						
quency Synthesizers						

Thesis 123141
M18966 McKaughan
c.1 Analysis of a proposed differential Omega system.